

PEQUANNOCK WTP
CORROSION CONTROL
REVIEW AND
RECOMMENDATIONS -
FINAL

City of Newark
Lead and Copper Rule Compliance Study
Newark, NJ

City of Newark Department of
Water and Sewer Utilities

March 15, 2019



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Section 1

Executive Summary

The City of Newark (Newark) exceeded the Lead and Copper Rule (LCR) Action Level for lead in the two sampling rounds in 2017 (January 2017 to June 2017 and July 2017 to December 2017) and in the first half of 2018 (January 2018 to June 2018). The Action Level for lead is 15.0 micrograms per liter ($\mu\text{g/L}$). The 90th percentile concentrations during these periods were as follows:

- January to June 2017 – 27.0 $\mu\text{g/L}$
- July to December 2017 – 26.7 $\mu\text{g/L}$
- January to June 2018 – 17.8 $\mu\text{g/L}$

Lead concentrations during these monitoring periods were higher in the Pequannock-supplied portions of the distribution system. The recent lead exceedances were the first in nearly 20 years of consistent compliance. The City first implemented sodium silicate for corrosion control treatment (CCT) in 1997; however, these recent lead exceedances indicate that the CCT at the Pequannock WTP is not currently optimized. Newark initiated a study in January 2018 to determine the causes of the recent exceedances.

This report addresses an assessment of the optimization of CCT for Newark's water supply. In January 2018, CDM Smith Inc. (CDM Smith), on behalf of Newark, commenced a corrosion control evaluation including the following studies:

- Statistical analyses and frequency distribution of lead data to understand the changing lead concentrations over time, and comparing the Pequannock and Wanaque systems
- Study of historic water quality trends impacting corrosion control
- Lead sequential sampling at selected residences in the system
- Pipe scale composition analyses performed by the United States Environmental Protection Agency (EPA)
- Lead solubility modeling

This report includes the results of these evaluations, which provide an understanding of the variability in water quality that occurred throughout recent history and the associated impacts on lead corrosion within Newark's system.

Historical Lead Concentrations

Figure ES-1 shows the frequency distribution of the historical LCR compliance sampling results on the Pequannock-supplied portion of the distribution system between 1992 and 2018. As can

be seen from **Figure ES-1**, lead results have increased significantly in the last three rounds, in some cases exceeding the original 1992 values prior to when CCT was implemented in 1997.

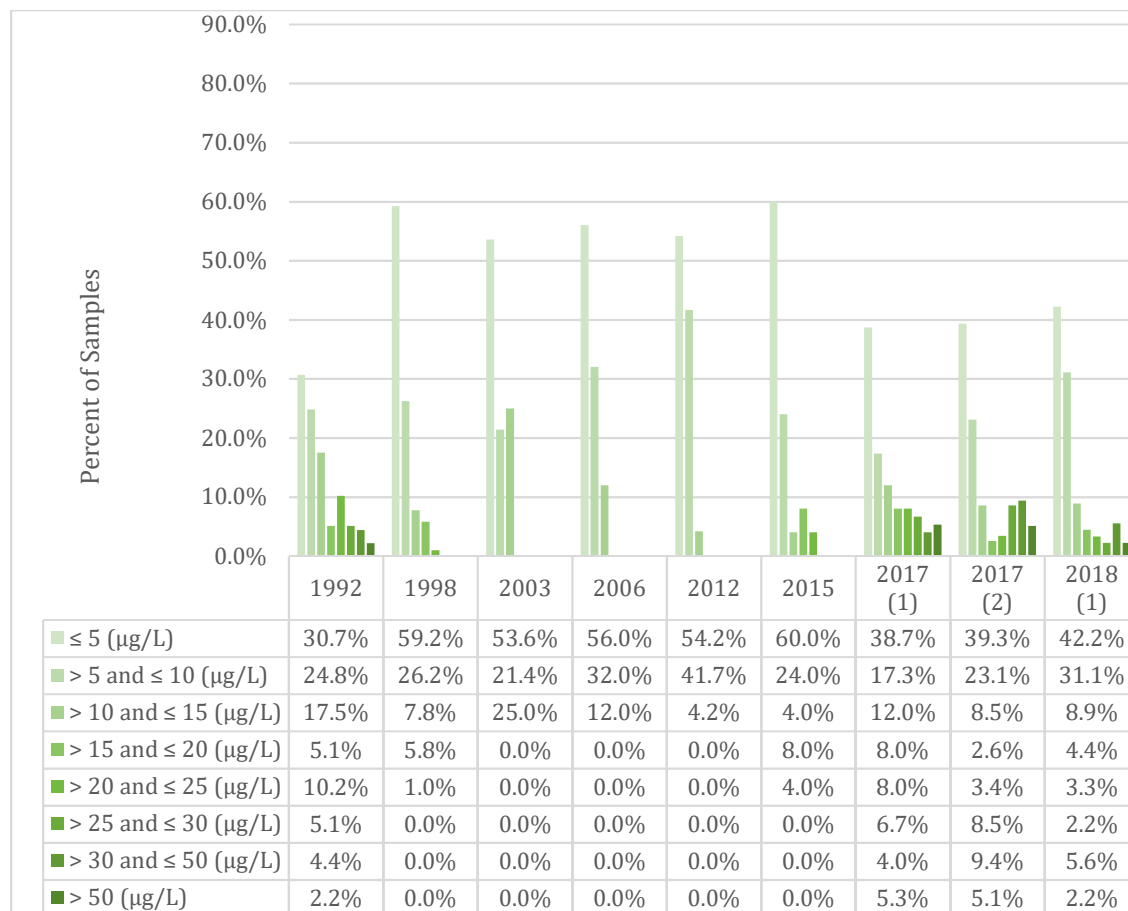


Figure ES-1 – Pequannock Service Area – Lead Sampling Data Percentage Frequency Distribution

Table ES-1 provides a summary of some statistical parameters based on the lead sampling compliance data in **Figure ES-1**.

Table ES-1 – Summary of Statistical Parameters for Pequannock Lead Sampling Data

Parameter	1992	1998	2003	2006	2012	2015	2017 (1)	2017(2)	2018 (1)
50th Percentile (µg/L)	8.5	4.0	4.8	4.1	5.0	0.0	7.4	7.8	6.4
75th Percentile (µg/L)	16.3	7.4	10.0	7.4	7.3	8.0	17.8	21.2	10.5
90th Percentile (µg/L)	26.8	12.3	12.2	9.5	9.7	15.8	29.8	36.0	22.9
Number of Samples (n)	137	103	28	25	24	25	75	117	90
Number of Samples >15 µg/L (n)	37	7	0	0	0	3	24	34	16
Percent > 15 & ≤ 25 µg/L	15.3%	6.8%	0.0%	0.0%	0.0%	12.0%	16.0%	6.0%	7.8%
Maximum (µg/L)	60.4	23.0	14.2	11.5	14.0	25.0	137.0	77.7	58.9

Scale Analysis

In February and March 2018, Newark took the initiative to send sections of three lead service pipes to the EPA Advanced Materials and Solids Analysis Research Core in Cincinnati, OH for characterization of the pipe scales. With the limited literature available and collective industry experience on sodium silicate, Newark understood the criticality of analyzing the pipe scales to gather more data specific to their system. Two of the pipes were excavated from the North Ward and one was excavated from the South Ward. After performing sequential sampling at Site A and Site B, sections of those lead service lines were also sent to the EPA Advanced Materials and Solids Analysis Research Core in October 2018 to compare the sample results with the scale analysis.

Analysis of pipe scales that reflect actual distribution system conditions provides a direct indication of the effectiveness of a current treatment protocol. Knowledge of the characteristics and behavior of the lead scales that have been formed in the service lines can be integrated with water quality, lead testing results and operational information to understand mechanisms of corrosion inhibition, speciation of metals and predictions of mobility/stability and can assist in implementation of corrective treatment changes. Knowing the chemical composition of a contaminant in distribution system scale materials can help with estimating the probability of unintended adverse consequences due to treatment or water quality changes.

Based on the testing performed by the EPA, the scales found on the outermost layers of the pipe walls were primarily hydrocerussite ($\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$), with cerussite (PbCO_3) and plattnerite (PbO_2) present as well. Hydrocerussite and cerussite are Pb(II) compounds that are carbonate-based scales. In carbonate-based scales, the hydroxide (OH^-), carbonate (CO_3^{2-}), or bicarbonate (HCO_3^-) ions bind with the metal (i.e., lead) to form metal/hydroxide/carbonate compounds of varying degrees of solubility on the interior wall of water pipes. Cerussite is the stable Pb(II) phase at pH 8–8.5. Cerussite is much more soluble than hydrocerussite, which is the stable Pb(II) phase at higher pH (≥ 9.0). It is unusual to find hydrocerussite as the dominant scale at Newark's current operating pH of around 7.4.

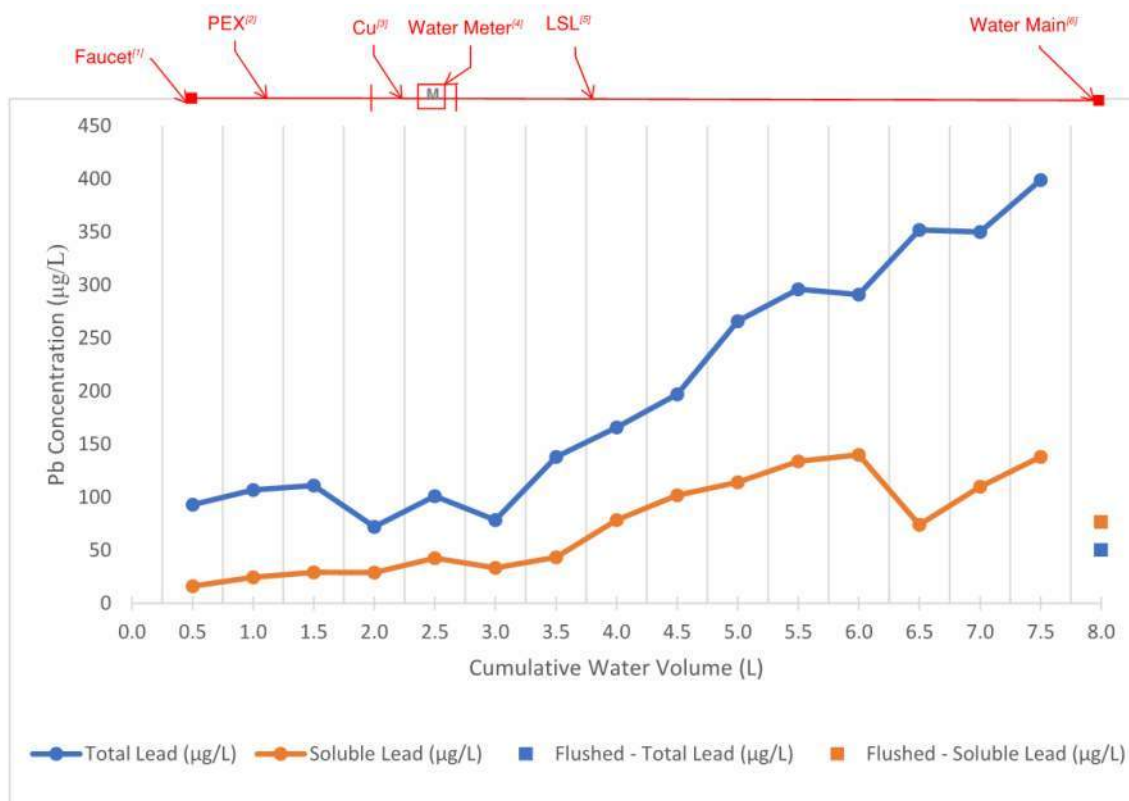
Plattnerite (PbO_2) is a Pb(IV) compound that is formed in waters with high redox potential (ORP). It is reported in the literature that a high ORP can be maintained when free chlorine is used (at levels typically over 1.5 mg/L), and that the rate of formation of PbO_2 appears to increase with increasing pH (Boyd, et al., 2008). Pb(IV) has also been observed in systems with free chlorine residuals less than 1.5 mg/L, including in Newark. Under these conditions, PbO_2 typically dominates or coexists with Pb(II) mineral forms, including hydrocerussite and cerussite. Plattnerite is appreciably less soluble than hydrocerussite and cerussite, making plattnerite more effective at maintaining low lead levels when the proper (high ORP) water chemistry is maintained.

The pipe scales did not contain any crystalline Si-Pb compounds, indicating that silicate complexation is not taking place and is not controlling soluble lead. However, a silica crust (SiO_2) was found on all three pipes. The silica crust was found to be porous and therefore was not acting as a barrier to the outward flux of lead from the pipe as the passivating layers (i.e. mainly plattnerite and hydrocerussite) were found forming behind, or closer to the pipe wall, than the silica crust.

The pH within the distribution system has a major impact on scale formation. In systems without orthophosphate, lead control relies on the formation of divalent lead carbonate scales or tetravalent lead (Pb(IV)) scales. For carbonate scales, such as cerussite and hydrocerussite, pH and alkalinity are critical parameters in their formation. For tetravalent lead, scale formation is dependent on pH, ORP and the presence of natural organic matter (NOM). Both types of scales were found in Newark's distribution system based on the scale analyses performed by the EPA.

Sequential Sampling

In September 2018, the City of Newark conducted sequential sampling at two locations with lead service lines (LSLs) and copper interior piping with lead solder. The purpose of this effort was to pinpoint potential sources of lead that exist within the service line and premise plumbing from the service connection in the street to the drinking water tap in the house. Sequential sampling is a tool to assist in developing an understanding of the system as part of the CCT optimization. The sources of lead at the tap measured in sequential samples can include LSLs, lead-based materials contained in the premise piping (e.g., leaded solder, brass/bronze fittings, galvanized piping), faucets, and water meters. The results are presented in Section 4 which indicate high lead levels of both soluble and insoluble forms in both the North and South Ward sampling locations. In comparison, higher lead levels were found in the South Ward location. **Figure ES-2** shows the sample results in a lead profile for the home tested in the South Ward compared with the associated plumbing component associated with that sample volume.



^[1] Kitchen Faucet Location, ^[2] Cross-Linked Polyethylene Pipe Segment, ^[3] Copper Pipe Segment, ^[4] Water Meter Location, ^[5] Lead Service Line Pipe Segment, ^[6] Water Main Location

Figure ES-2 – Site A – South Ward Lead Profile – September 10, 2018

In conclusion, the sequential sampling performed at opposite ends of Newark's distribution system show that the current corrosion practice is not optimized at controlling soluble lead release into the drinking water. Despite the silica concentrations in the water of approximately 8 mg/L as SiO₂ and the presence of a silica crust found in the EPA scale analysis (presented in Section 5), soluble lead was well above the EPA's lead Action Level. In addition, if a passivating scale was intact and functioning as a protective scale, lead levels would be expected to be much lower (Boyd, et al., 2008) than what was found.

The results confirm that the scales found on the pipes from the EPA scale analyses are not functioning as protective corrosion control scales under the current water quality conditions. Regarding particulate lead, both locations have appreciable particulate lead in the samples. This could be a result of sediment in the service line, particulates that collected in the aerator during the flushing prior to the stagnation period, active breakdown of the lead scale, some recent plumbing work performed by the homeowner, or most likely a combination of these factors.

Potential Causes of Recent Lead Exceedances

Based on the analyses performed over the course of this study, the following factors are most likely to have influenced the 2017-2018 elevated lead levels in Newark's distribution system. These are described in more detail in Section 6 as well as other possible contributing factors.

- Decrease in pH in the distribution system
- LCR compliance sampling

pH has fluctuated substantially for the delivered water, or distribution system point-of-entry (POE) measured at the "Test House", from the Pequannock WTP between 1992 and 2018 as shown in **Figure ES-3**. pH was maintained above 8.0 for several years. Starting in 2016, however, the pH declined to the current average of approximately 7.1.

Because both Pb(II) scales and Pb(IV) scales were found on Newark's LSLs and reducing pH negatively affects the formation of insoluble scales for both forms of lead, the reduction in pH in the Newark distribution system is likely the main cause for the 2017 and 2018 elevated lead levels. Raising pH to levels that will provide the desirable water chemistry for these scales to re-stabilize will risk Newark's ability to simultaneously comply with primary disinfection (CT) and disinfection byproduct regulations. Hence, returning to the corrosion control strategy Newark employed in the 1990s and early 2000s to comply with the LCR is no longer considered a viable option without other system upgrades to meet all regulations simultaneously.

It is not possible to confirm the exact duration of the elevated lead levels in Newark's distribution system. An underlying issue may have been developing that may not have been captured or discoverable in compliance sampling since testing was limited to first draw samples, as required by the regulations. This is discussed further in Section 6.

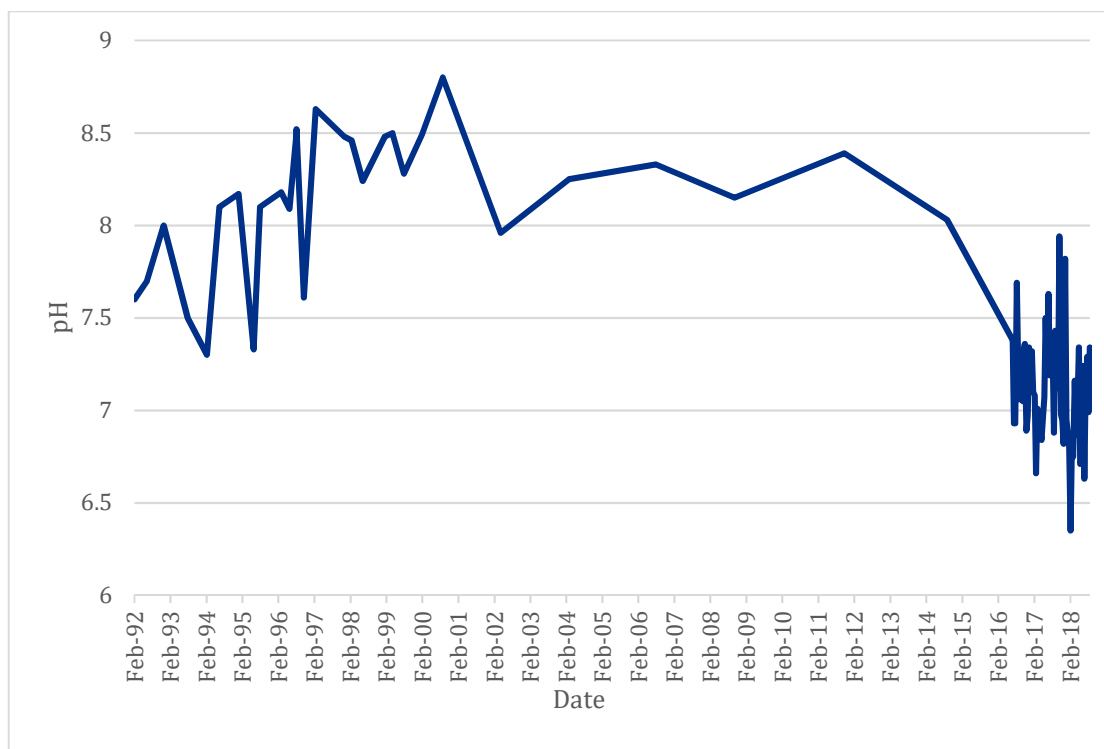


Figure ES-3 – Historic Pequannock WTP Delivered Water pH

Recommendations

With the results of the analyses performed in this study, several alternatives are recommended to reduce lead levels in the distribution system. The addition of orthophosphate is recommended to significantly reduce lead solubility without any adverse impacts on other water quality goals, e.g., without impacting simultaneous compliance with primary disinfection and disinfection byproduct regulations. The recommendations are summarized in **Table ES-2** and described in more detail in Section 8. The recommendations address both short-term implementation as well as long-term, sustained compliance with the LCR.

Table ES-2 – Summary of CCT Recommendations

Factor	Immediate CCT Recommendation	Longer Term CCT Recommendation	Additional Notes
Chemical	Zinc Orthophosphate	Zinc Orthophosphate	
Dosage	0.5 mg/L as PO ₄ increasing to passivation dose of 3.0 mg/L as PO ₄	Minimum 1.0 mg/L as PO ₄ (or as determined by pipe loop study)	Evaluate dosage in pipe loop study
Feed Location	Valley Road Rechlorination Station	Valley Road Rechlorination Station	
System pH	Stabilize pH to 7.3 to 7.4	Stabilize pH to optimal pH from pipe loop study	Evaluate optimal pH in pipe loop study
Sodium Silicate	Maintain current dose	Replace with a more cost-effective pH adjustment chemical	Evaluate any negative impacts from eliminating sodium silicate addition in pipe loop study

Factor	Immediate CCT Recommendation	Longer Term CCT Recommendation	Additional Notes
Demonstration Study	Conduct pipe loop study in parallel with implementation of immediate addition of zinc orthophosphate	Apply results of pipe loop study to long-term CCT plan	
Monitoring	Implement representative monitoring program, including sequential sampling	Continue monitoring program and sequential sampling until conditions are stabilized	
Public Health	Point-of-use filters and conduct public education program	CCT optimization and LSL Replacement Program	

Section 2

Background

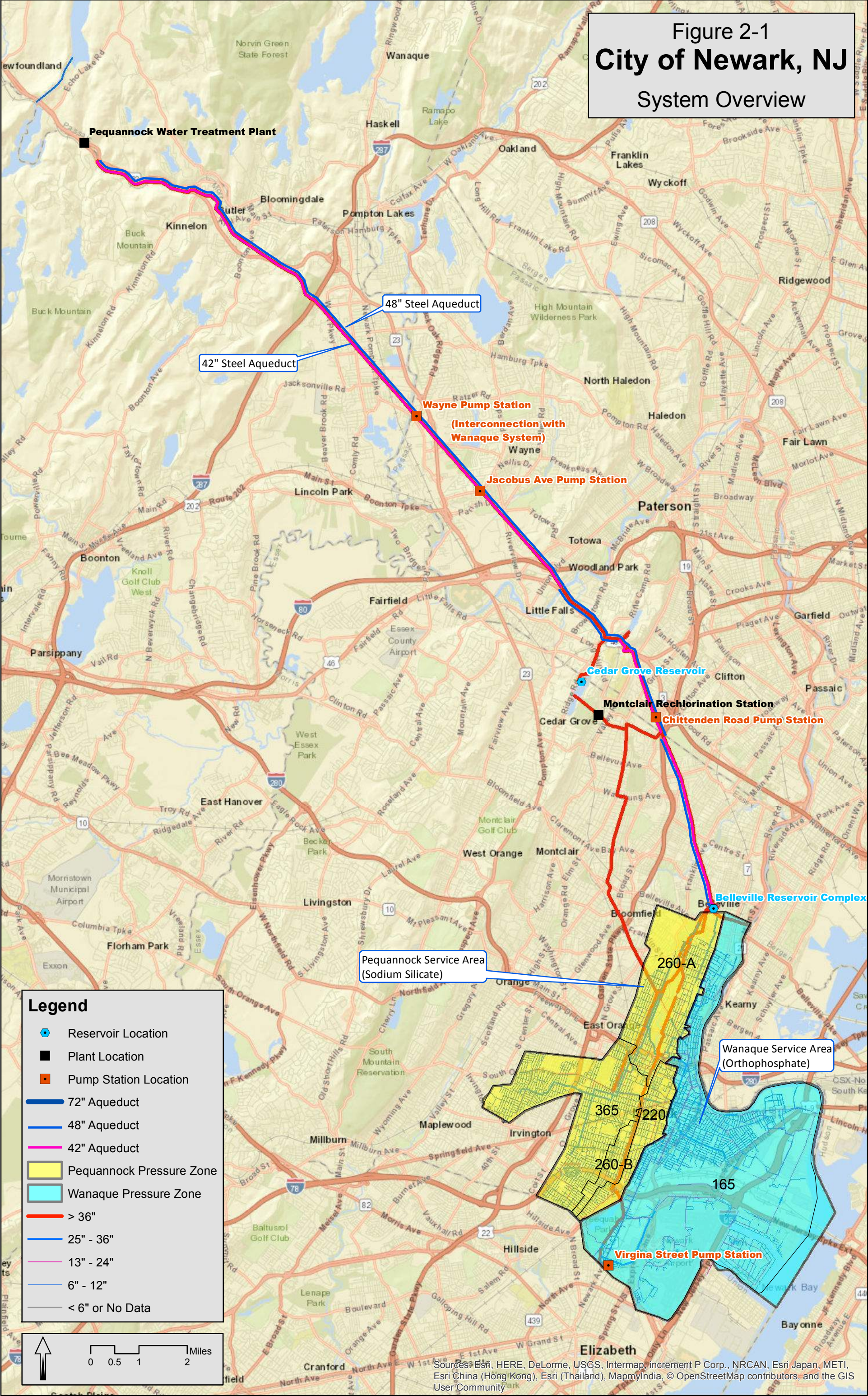
The City of Newark (Newark) supplies approximately 80 million gallons per day (mgd) of potable water to a population of over 300,000 customers located in Newark, NJ and its surrounding communities. Newark's population of approximately 280,000 is supplied potable water through a large, complex system that is managed by the City of Newark's Department of Water and Sewer Utilities (Department).

Newark utilizes two sources to supply their distribution system. The Pequannock Water Treatment Plant (WTP), located in West Milford, NJ, supplies approximately 40 mgd primarily to Newark's West Ward and most of the North, South and Central Wards, or the "higher" pressure gradients above 200 feet as shown in **Figure 2-1**. The Pequannock WTP treats surface water from the Charlotteburg Reservoir. The Pequannock WTP processes include pre-chlorination (for oxidation), coagulation, direct filtration with dual media filters, post-pH adjustment with lime, disinfection with chlorine gas, and sodium silicate addition for corrosion control. Treated water flows from the Pequannock WTP through a 72-inch aqueduct which splits into dual 48-inch and 42-inch steel aqueducts to the open, approximately 675 million-gallon (MG) Cedar Grove Finished Water Reservoir. The water then travels by gravity through the Valley Road Rechlorination Station in Montclair where it is rechlorinated prior to supplying Newark's water distribution system's higher-pressure gradients.

The other water source for Newark is from the Wanaque WTP operated by the North Jersey District Water Supply Commission (NJDWSC), which supplies the East Ward, and portions of the North and Central Wards (pressure gradient of 165 ft and below) as shown on **Figure 2-1**. The Wanaque WTP is a conventional WTP with coagulation, clarification, and filtration and delivers water to Newark via two paths. The first is through the Wayne Pump station, which delivers up to 38 mgd, typically between 10 and 15 mgd, of treated water from the Wanaque WTP to the Pequannock system upstream of the Cedar Grove Reservoir, allowing it to supply the higher-pressure gradients. The Wanaque supply that is blended with the Pequannock supply is fully treated except for corrosion inhibitor. Wanaque water is also fed to Newark's lower pressure gradient through the Belleville Reservoir Complex at approximately 25 to 28 mgd. Upstream of the Belleville Reservoir Complex, zinc orthophosphate is added. This water feeds the lower pressure gradient (East Ward) in Newark's distribution system.

During the January to June 2017 Lead and Copper Rule (LCR) sampling round, Newark exceeded the Action Level (AL) for lead at the 90th percentile, based on a total number of samples of 233 customers. On July 11, 2017, the New Jersey Department of Environmental Protection (NJDEP) sent a letter to Newark that outlined a series of required actions in response to the Lead Action Level exceedance. Of the requirements, NJDEP required Newark to submit an Optimal Corrosion Control Treatment (OCCT) recommendation in accordance with 40 CFR 141.82(a) no later than six (6) months after the monitoring period when the action level was exceeded, or by December 31, 2017.

Figure 2-1
City of Newark, NJ
System Overview



In response to NJDEP, Newark submitted an OCCT Memorandum on December 27, 2017. The 2017 OCCT Memorandum outlined the following recommended actions:

- Continuing to collect the Water Quality Parameter data “to ensure proper corrosion control treatment”
- Completion of a corrosion control optimization desktop study
- A coupon study at several locations in the distribution system
- Pipe loop testing

The 2017 OCCT Memorandum set the following as target Water Quality Parameters (WQPs) to be maintained for the Pequannock system:

- pH over 7.2
- Alkalinity over 30 mg/L
- Silica over 6.0 mg/L as SiO₂

Newark also stated they would increase the sodium silicate dose to 12-15 mg/L from 8-12 mg/L, effective July 24, 2017.

Since the 2017 OCCT Memorandum was issued, Newark has exceeded the Lead Action Level in the second half of 2017 and the first half of 2018. Newark is currently evaluating both immediate and long-term measures to minimize lead levels throughout the system. Specifically, Newark is looking to: a) implement a program to replace all lead service lines in Newark; and b) optimize corrosion control treatment. Newark’s initiative to replace all lead service lines in the City is being performed under a separate project and is not discussed in this report.

This report addresses the optimization of corrosion control treatment for Newark’s water supply. Provided herein are the results of CDM Smith’s evaluations of historic and current water quality in the source water and distribution system. These evaluations provide an understanding of the variations in water quality that occurred throughout recent history and the associated impacts on lead corrosion within Newark’s system. With this understanding, several alternatives were considered to reduce lead solubility in the distribution system. Recommendations are provided for short-term implementation as well as long-term, sustained compliance with the LCR.

2.1 Current Corrosion Control Treatment (CCT)

The Pequannock WTP has dosed sodium silicate at the plant since 1997, based largely on the Corrosion Optimization Study prepared by the City of Newark in June 1994. The Wanaque WTP has dosed zinc orthophosphate upstream of their Belleville Reservoir Complex since the mid-1990s. Details on the current CCT implemented in both water supplies are discussed in this section of the report.

2.1.1 1994 Corrosion Optimization Study

When the LCR was established in 1991, both the Pequannock and Wanaque systems experienced high lead levels when performing the initial requisite monitoring programs in 1992 and 1993. At that time, both systems commenced corrosion control studies and implemented corrosion control treatment (CCT) in the mid- to late-1990s.

The Pequannock WTP implemented CCT based on a study performed by the Division of Water/Sewer Utility and summarized in a report, “City of Newark Report on Corrosion Optimization Study,” dated June 1994. The study included bench-scale testing and a pipe loop study evaluating the effectiveness of the following corrosion inhibitors:

- Increased lime (to increase pH)
- Orthophosphate
- Ortho-poly blended phosphate
- Sodium silicate

The bench-scale testing involved a two-cell corrosion test device where raw water was fed into the first cell and mild steel metal coupons were suspended in both cells. A corrosion inhibitor was applied to the water before it entered the second cell (Newark, 1994). The anticipated percent reduction of lead leaching for each of the inhibitors was estimated based on a function of weight loss by the mild steel coupons which were used as a surrogate for lead. The estimated reductions were as follows:

- 15% reduction for lime, pH 8.5 to 9.0 maintained
- 50% reduction for zinc orthophosphate based on a dose of 1 mg/L as PO_4 (pH not specified)
- 40% reduction for ortho-polyphosphate blend (dose and pH not specified)
- 45% reduction for silicate based on a dose of 20 mg/L as SiO_2 for 1 month and a dose of 9 mg/L as SiO_2 (pH not specified)

The bench-scale tests were followed by pipe loop experiments. The pipe loops had new ½-inch lead and copper piping and flow was maintained at 1 gallon per minute (gpm) to simulate typical flow in a home. The loops were run without any addition of a corrosion inhibitor for the first 6 weeks at a pH of approximately 7.3. By the end of the 6 weeks, the pipe loops were considered “stabilized” and results were showing consistent water quality characteristics across all six (6) pipe loops, including lead concentrations (Newark, 1994). Subsequent testing was performed with orthophosphate and an ortho-polyphosphate blend for 26 weeks and with silicate for 40 weeks. Sodium silicate was tested at dosages ranging from 8 mg/L to 24 mg/L, which raised the pH of the water to between 8.4 and 9.0 (Thompson, 1997). Although not specifically stated in the study, it is assumed that the dosages are presented in units “as silica (SiO_2)”. If the dosages were “as silica,” then the “as sodium silicate product” dose would be approximately three (3) times these values, or 24 mg/L and 72 mg/L, respectively. The silicate treatment proved to be effective

under these conditions, reducing lead release from lead pipe by 65% and from lead-soldered copper pipe by 60% over the control.

Orthophosphate also proved to be effective at a pH of 7.4 to a similar degree as the silicate, but was eliminated since it could not be dosed at the plant upstream of the Cedar Grove Reservoir without risking algae growth in the open reservoir. At the time, the author of the study stated that the City would have to construct “a number of satellite feeding stations which may involve substantial capital improvements and, hence, create a liability to the City’s financial implication.” (Newark, 1994). At the time, the City was providing treated water to other municipalities upstream of the Cedar Grove Reservoir. Currently, only the Township of Pequannock is fed upstream of the Cedar Grove Reservoir, other than emergency interconnections.

The 1994 report noted that Newark also had concerns with phosphates due to a prior experience involving water complaints following the addition of a polyphosphate blend at the Pequannock WTP for 2 years in the mid-1980s. Newark stopped using the polyphosphate due to these complaints, as well as severe algae growth in the Cedar Grove Reservoir (Newark, 1994).

Newark ultimately recommended sodium silicate as the optimal corrosion control treatment, at a starting dose of 18-20 mg/L for an initial passivation period then decreasing to an 8 mg/L maintenance dose (Newark, 1994). It is believed that the recommended dose was provided “as silica (SiO₂)”. The raw water silica concentration was reported to be 4.0 mg/L (Newark, 1994); therefore, the residual silica concentration would be expected to be approximately 12 mg/L in the finished water. No final pH was recommended; however, the pipe loop testing was performed at a pH of 8.5 to 9.0, which was achieved through the addition of lime and silicate.

Research on sodium silicate was limited at the time of the 1994 report. Since that time, it is believed that silica does not complex with lead in a similar manner to orthophosphate which forms lead compounds with low solubility (Taylor, et al., 2008). Instead, silicate helps to raise the pH which promotes the formation of lead-carbonate scales at higher pH values. See Section 7 regarding sodium silicate research and available literature.

2.1.2 Treatment Modifications Impacting Corrosion Control Since 1994

In 2003-2004, the Pequannock WTP supply was reduced from approximately 50-60 mgd to 40-45 mgd in order to reduce loading rates on the filters to meet stricter regulations on turbidity and disinfection byproducts. The difference was made up by increasing the Wanaque supply at the Wayne Pump Station to its current 10 to 15 mgd, which is blended with the Pequannock water and distributed to customers in Newark’s high-pressure gradients. The Wanaque water does not have any corrosion inhibitor when it is blended with the Pequannock water at Wayne. This dilutes the sodium silicate concentration prior to distribution to customers downstream of the Cedar Grove Reservoir. Based on our review of operational records, it is unclear if the sodium silicate dose was increased to account for the additional flow from Wanaque or if the effective feed rate to the Pequannock WTP supply was reduced, subsequently reducing the dose in the blended water.

Other changes to treatment that have occurred at the Pequannock WTP since the original pipe loop testing include:

- Between 2015 and 2018, finished water pH was maintained at the Pequannock WTP at approximately 6.9 to 7.3. The finished water pH is currently maintained below 7.4 and is averaging below 7.0 in order to achieve primary disinfection (CT) and minimize formation of disinfection byproducts. In the late 1990s, pH was maintained around 8.5 based on the recommendations from the 1994 pipe loop study. See Section 3.3, Historic Water Quality Trends, for additional information on pH over time.
- The quicklime system was replaced with a hydrated lime system in April 2017. Although upgrades were subsequently made to the hydrated lime system to improve performance and output in September 2018, **the primary driver for the lower pH is the need to meet primary disinfection requirements and not a result of equipment failures.**
- The current sodium silicate system occasionally struggles to meet the desired dose of 12 to 15 mg/L as sodium silicate for corrosion control. On average, a dose of 7 mg/L is applied to keep pH at a lower value to meet disinfection requirements.

2.1.3 Current Corrosion Control Treatment

Pequannock Supply

As noted above, the water supply to Newark's higher-pressure gradients (above 200 feet) is a blend of treated water from the Pequannock WTP and Wanaque water that is fed at the Wayne Pump Station upstream of zinc orthophosphate addition to the Wanaque supply. The Pequannock pressure gradients include almost all homes located in the West and South Wards and a majority of homes located in the Newark's North and Central Wards. As a result of the recent lead exceedances in these areas, Newark increased the sodium silicate dose from 8-12 mg/L to 12-15 mg/L as sodium silicate, or as close as possible to this dose with the existing equipment, in July 2017. The target dosage was equivalent to approximately 3.5-4.4 mg/L as silica (SiO_2), approximately half of the recommended dose from Newark's 1994 study. If Newark was to double the sodium silicate dose, the pH would increase accordingly, potentially creating issues with Stage 2 Disinfection Byproduct Rule compliance and meeting primary disinfection requirements at the plant. The sodium silicate target dose can be difficult to maintain during the cold winter months while consistently also meeting disinfection requirements since sodium silicate raises pH.

In the 2017 OCCT Memorandum, Newark stated that their target is to maintain a residual silica concentration of 6 mg/L throughout the distribution system. The silica concentration is measured in the plant finished water (Test House) and in the distribution system on a bi-weekly basis. Since the raw water provides approximately 4.0 mg/L of naturally occurring silica (Newark, 1994), only an additional 2 mg/L of silica (or approximately 6.9 mg/L of sodium silicate) is required to be added to meet this target. When the silicate treatment was first initiated, it is assumed that the silica concentrations in the distribution system would likely have been closer to 12 mg/L (approximately 8 mg/L from the sodium silicate and approximately 4 mg/L from the raw water). If the report recommendations were followed, the initial silica residual would have been 28 mg/L (24 mg/L from the sodium silicate and approximately 4 mg/L from the raw water). No data is available to confirm the initial dose of silicate or the initial silica residuals in the distribution system when the corrosion control treatment was first implemented.

Wanaque Supply

Newark's 165-foot pressure gradient is primarily comprised of the East Ward and small sections within the North, Central and South Wards. The 165-foot pressure gradient is supplied by water treated at the Wanaque WTP. The Wanaque supply to this system has been adding zinc orthophosphate upstream of the Belleville Reservoir Complex, but downstream of the Wayne Pump Station, since the mid-1990s. The Wanaque system maintains a pH of approximately 7.6 and doses approximately 1.2 mg/L as orthophosphate. This area has experienced much lower lead concentrations since implementing CCT in the 1990s than the regions supplied by the Pequannock WTP. Therefore, this study focuses on the sections of the distribution system supplied by the Pequannock WTP, as shown in **Figure 2-1**.

Recent CCT Optimization Efforts

In February 2018, CDM Smith Inc. (CDM Smith), on behalf of Newark, commenced a corrosion control evaluation including the following studies:

- Statistical analyses and frequency distribution presentations to understand the changing lead concentrations over time, and comparing the Pequannock and Wanaque systems
- Study of historic water quality trends impacting corrosion control
- Lead sequential sampling at residences in areas of concern in Newark's distribution system
- Pipe-scale composition analysis performed by the United States Environmental Protection Agency (EPA) of pipes located in areas of concern in the system
- Lead solubility modeling

The results of these studies are provided in this report in Sections 2.3, 3, 4, 5 and 7.

2.2 Lead and Copper Rule Compliance Sampling Results

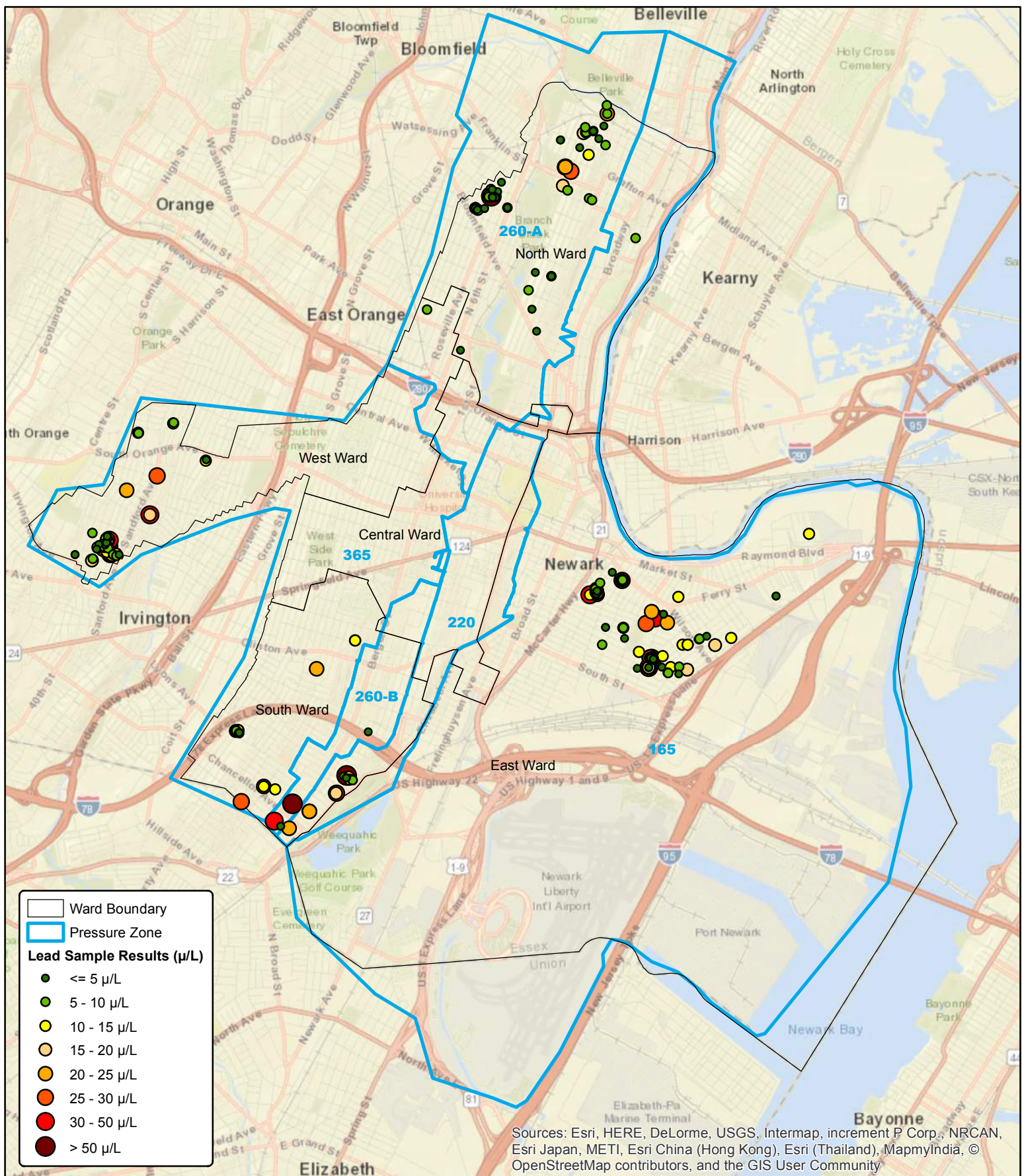
As discussed above, due to consecutive rounds of Lead Action Level exceedances in 1992 (90th percentile above the Action Level of 15 µg/L), both the Pequannock and Wanaque systems implemented CCT in the 1990s. After 1992, water quality data is available for the subsequent residential LCR compliance sampling performed in 1998, 2002, 2003, 2006, 2009, 2012, 2015, 2017, and the first half of 2018. The second round of sampling in 2018 (from July to December) is ongoing at the time of the preparation of this report. This analysis focuses on residential sampling. Additional sampling has been performed at schools with similar results.

Maps showing the locations and lead concentrations for all compliance sampling events, including the initial sampling in 1992 leading to implementation of CCT, are provided in **Figures 2-2 through 2-12**. As shown in the figures, Newark did experience a period with very low lead concentrations in their sampling pool between 1998 and 2012. During this period, the compliance sampling locations varied. **For example, in 2002 and 2009, only homes receiving Wanaque water were sampled. In 1998 and 2006, only homes receiving Pequannock water were sampled.** In 2015, slightly elevated lead concentrations were found, but they were still below the Action Level. During the subsequent sampling rounds, lead levels exceeded the Action Level during the first and second half of 2017, as well as the first half of 2018. The Action Level was also

exceeded in the last two sampling rounds by Newark's consecutive system, Bloomfield, which receives a large percentage of its supply from Newark's Pequannock WTP.

As corrosion control chemistry transitions are a slow process, it cannot be determined exactly when the lead levels started to increase. To monitor the transition of potential high lead levels, Newark has followed the acceptable practice of maintaining routine monitoring of the WQPs, as well as, continuing tap sampling under the LCR.

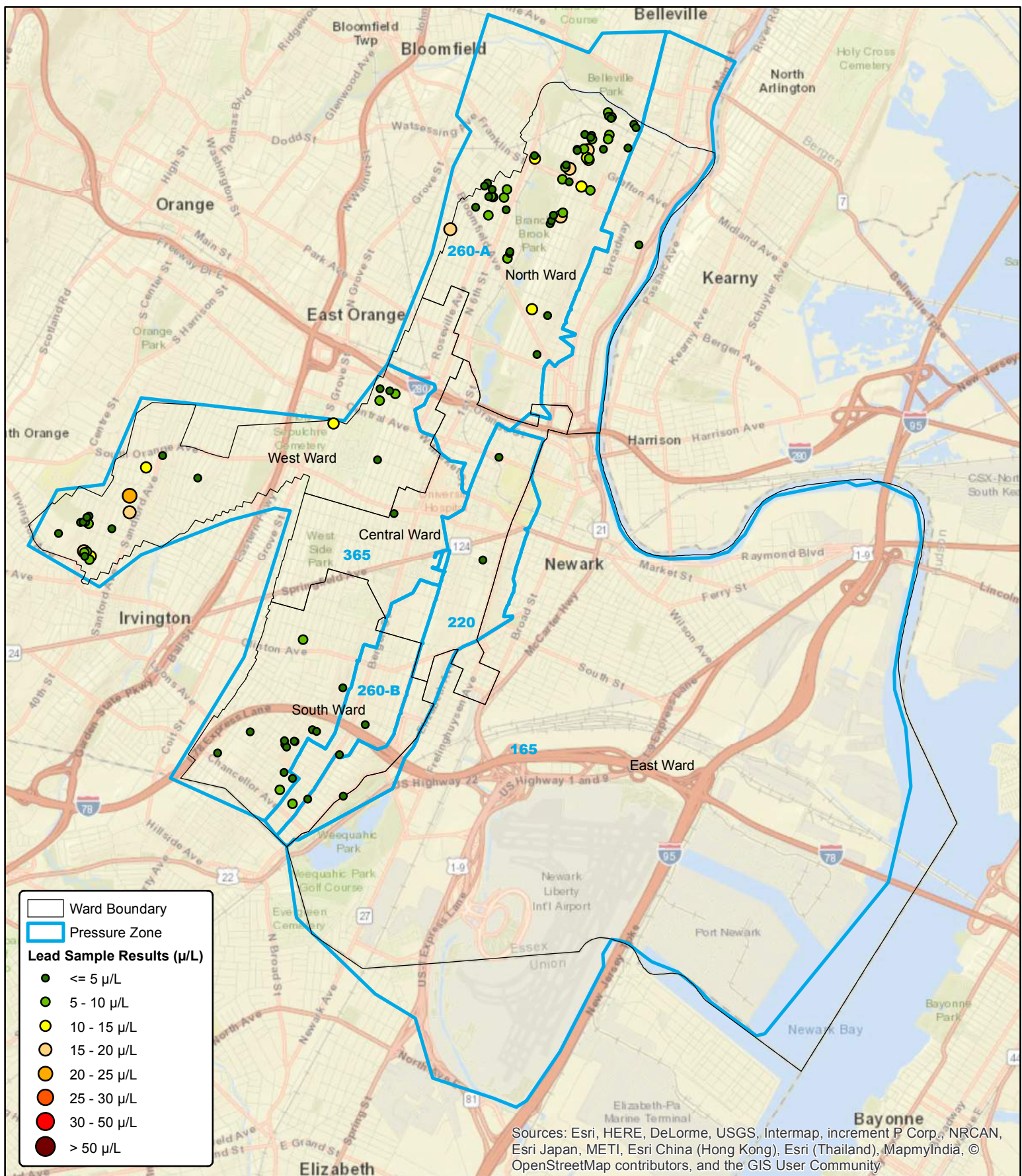
The LCR Action Level for copper is 1.3 mg/L at the 90th percentile value. Newark has not experienced high copper levels in their system based on the data analyzed. Optimization of treatment for copper, therefore, is not addressed in this report.



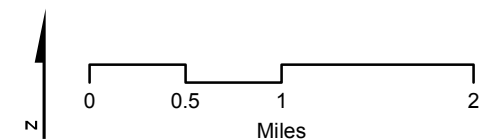
Lead Level in the City of Newark

Data Collected: 1992

Figure 2-2



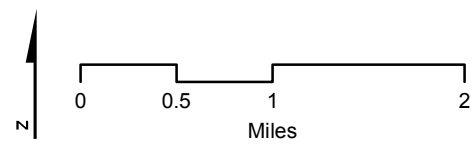
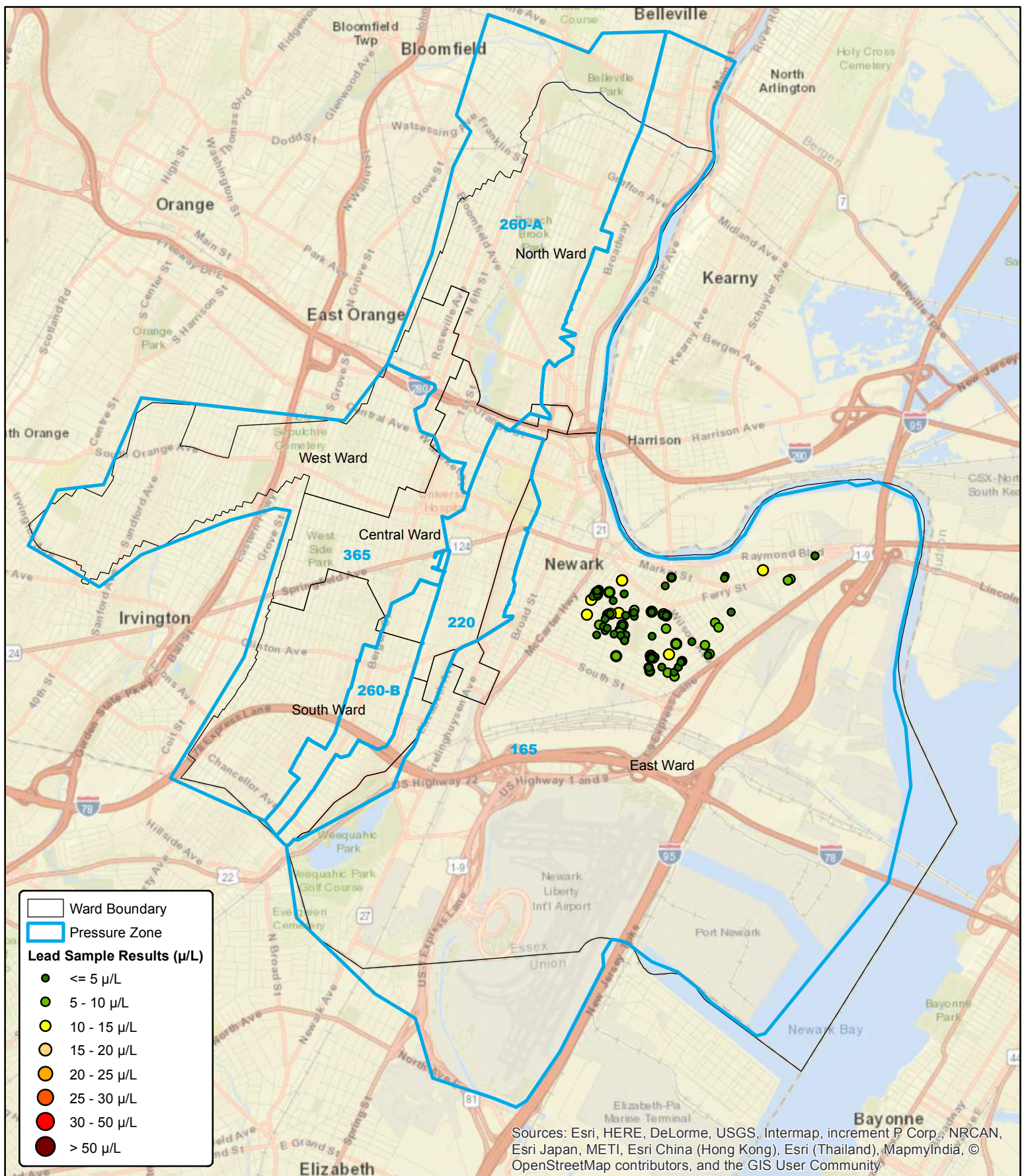
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community



Lead Level in the City of Newark

Data Collected: 1998

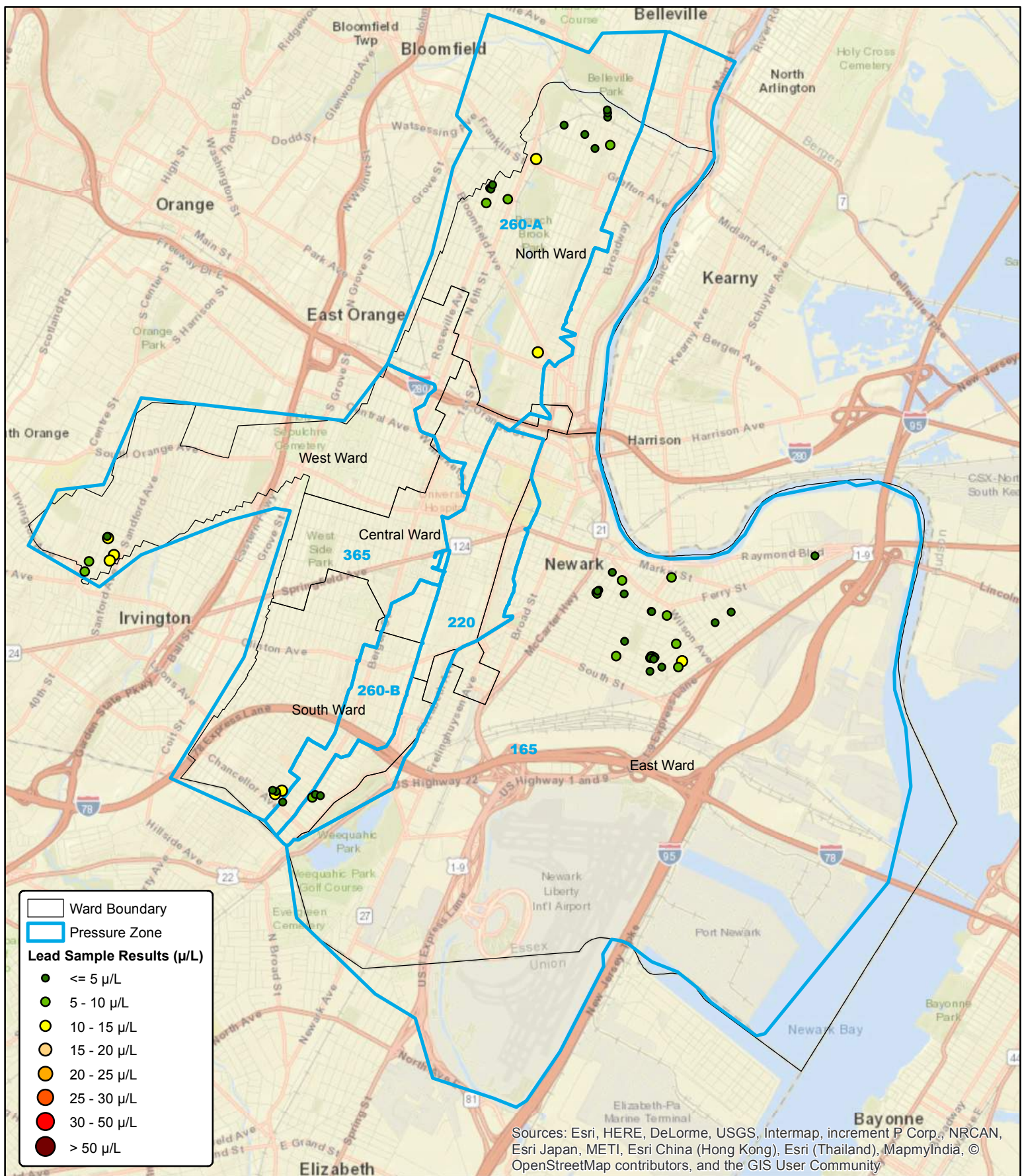
Figure 2-3



Lead Level in the City of Newark

Data Collected: 2002

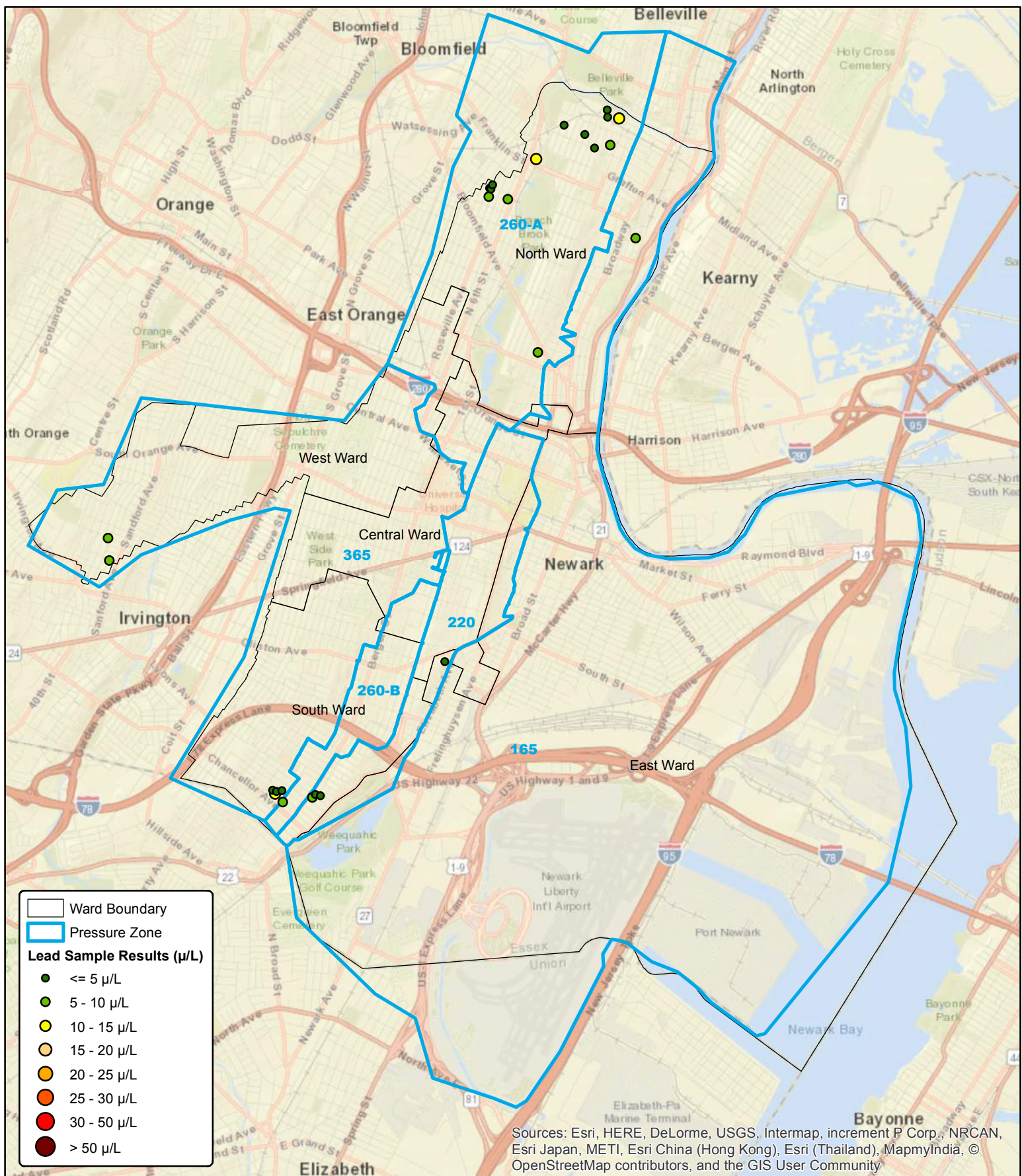
Figure 2-4



Lead Level in the City of Newark

Data Collected: 2003

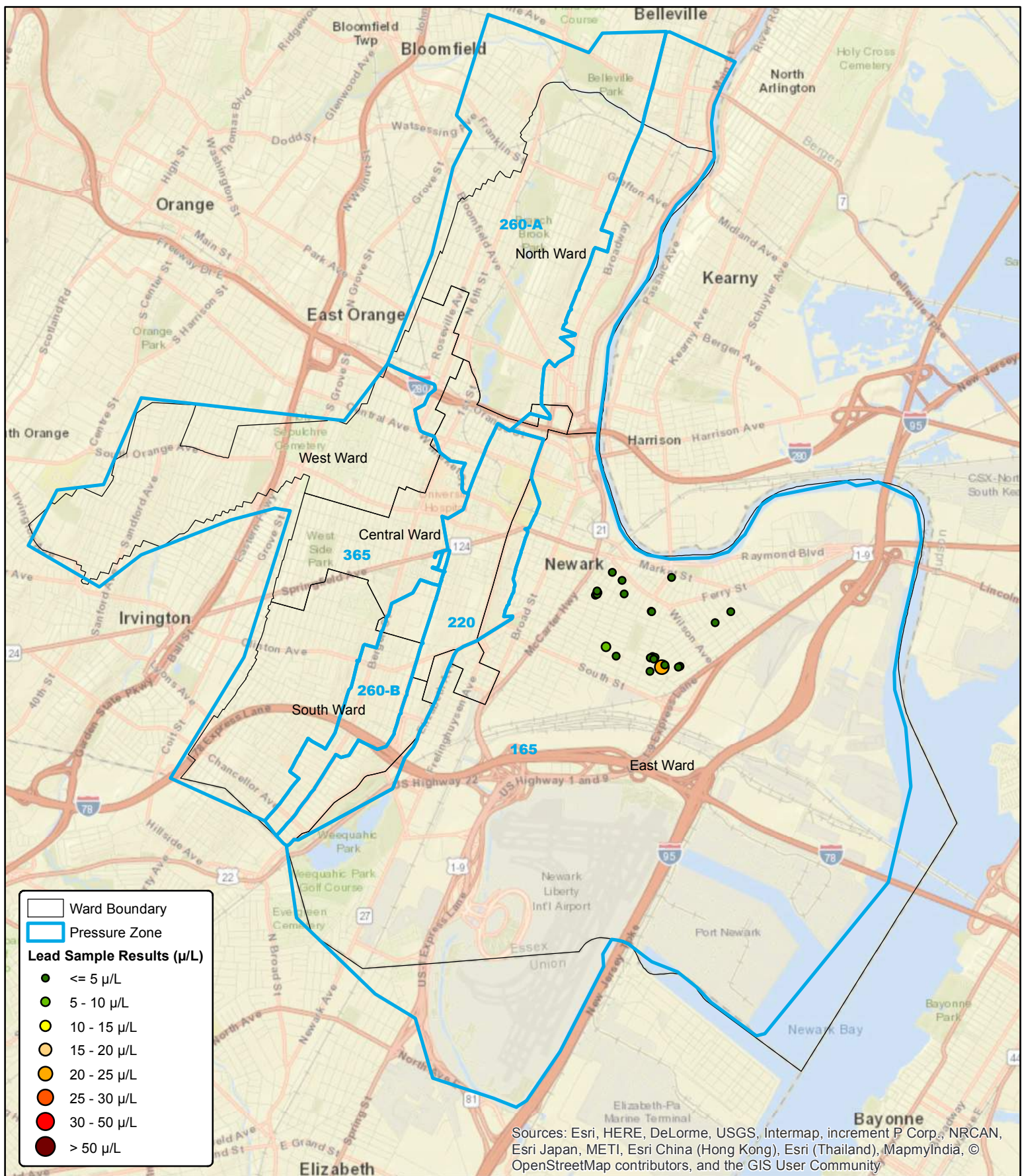
Figure 2-5



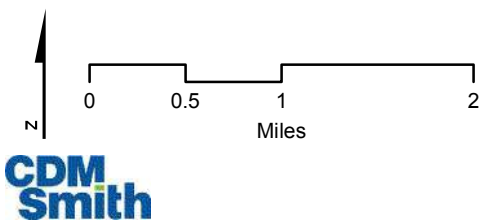
Lead Level in the City of Newark

Data Collected: 2006

Figure 2-6



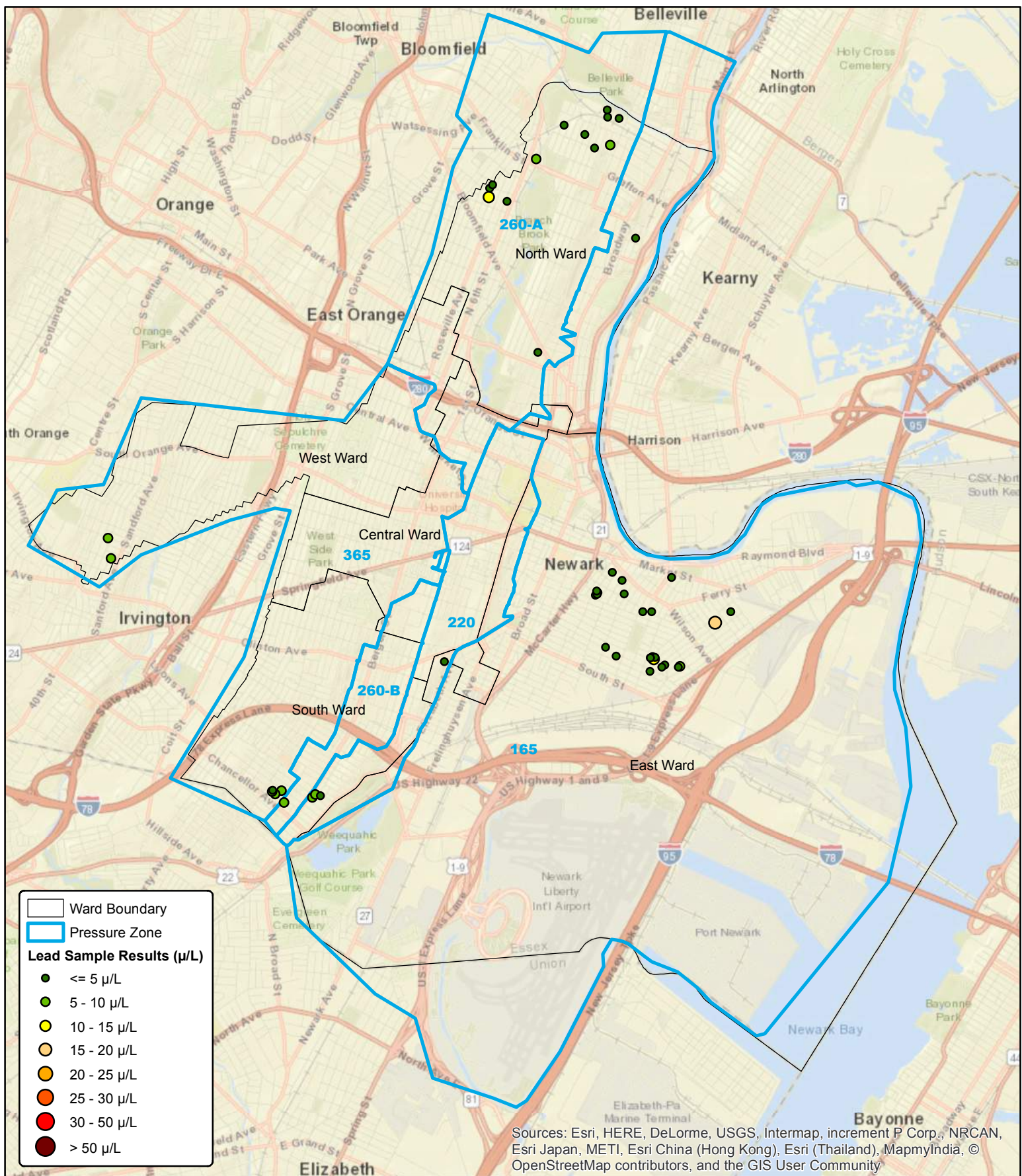
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community



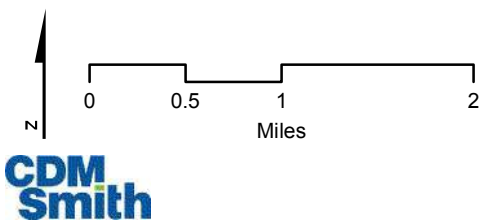
Lead Level in the City of Newark

Data Collected: 2009

Figure 2-7



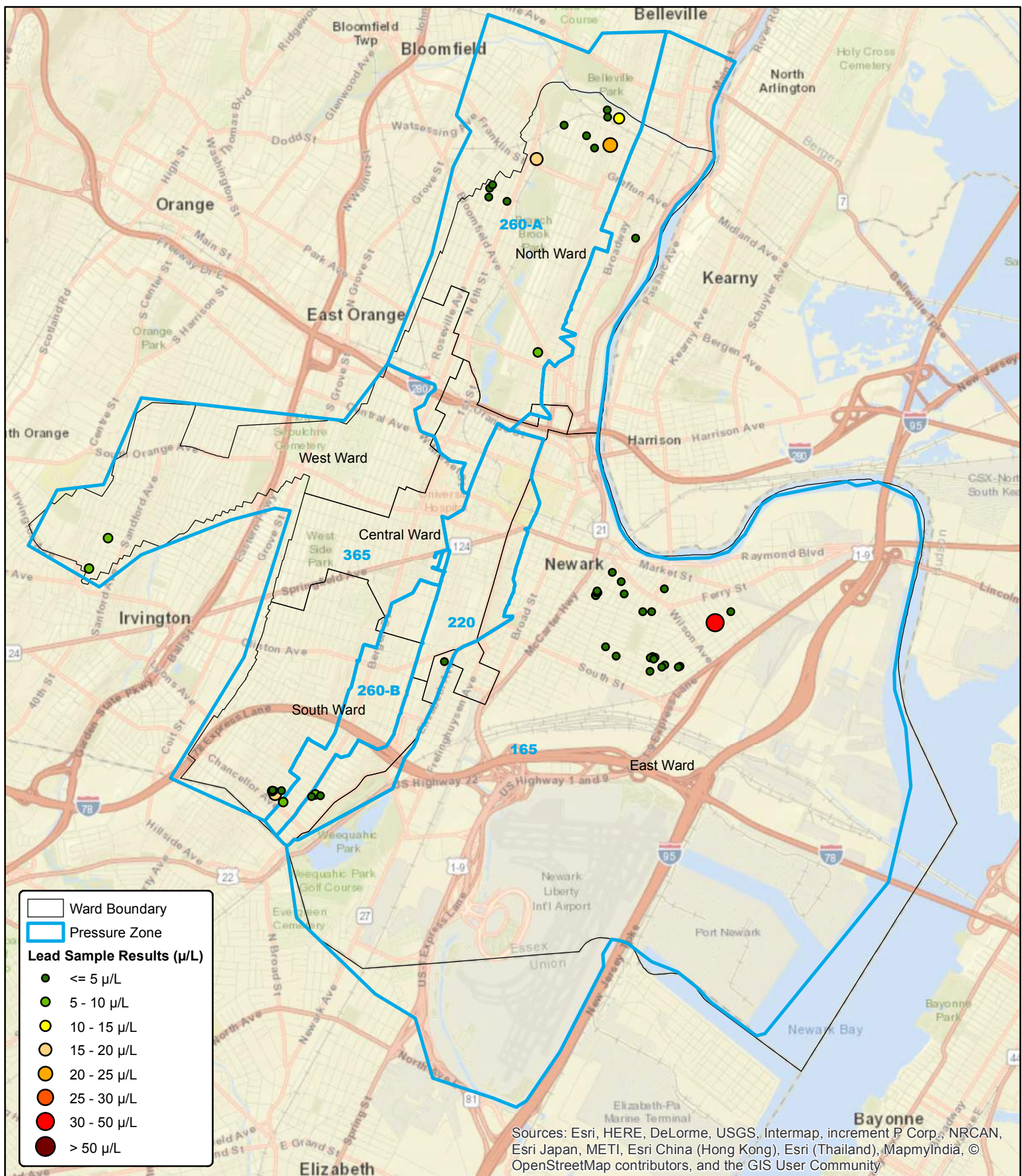
Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), MapmyIndia, © OpenStreetMap contributors, and the GIS User Community



Lead Level in the City of Newark

Data Collected: 2012

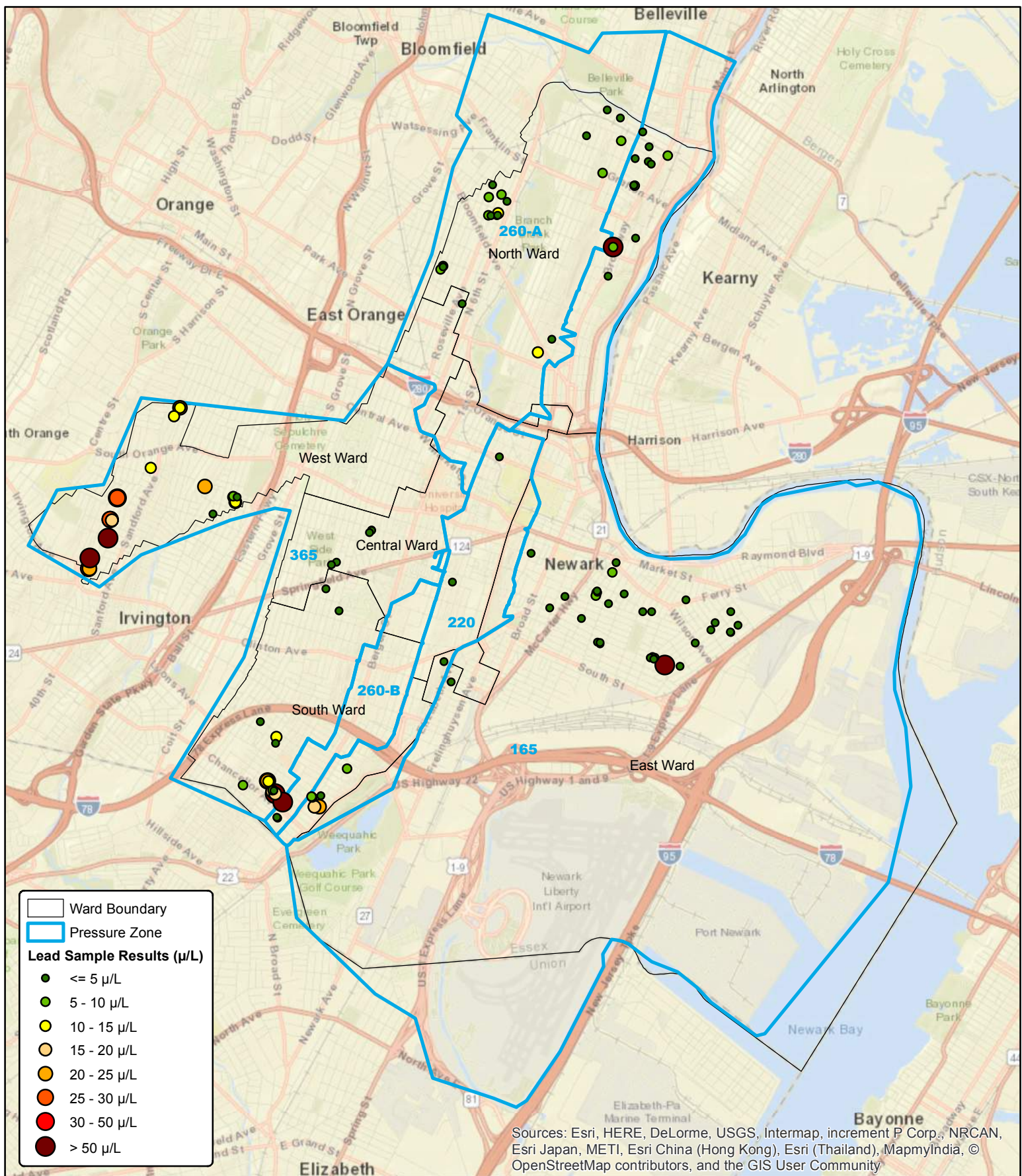
Figure 2-8



Lead Level in the City of Newark

Data Collected: 2015

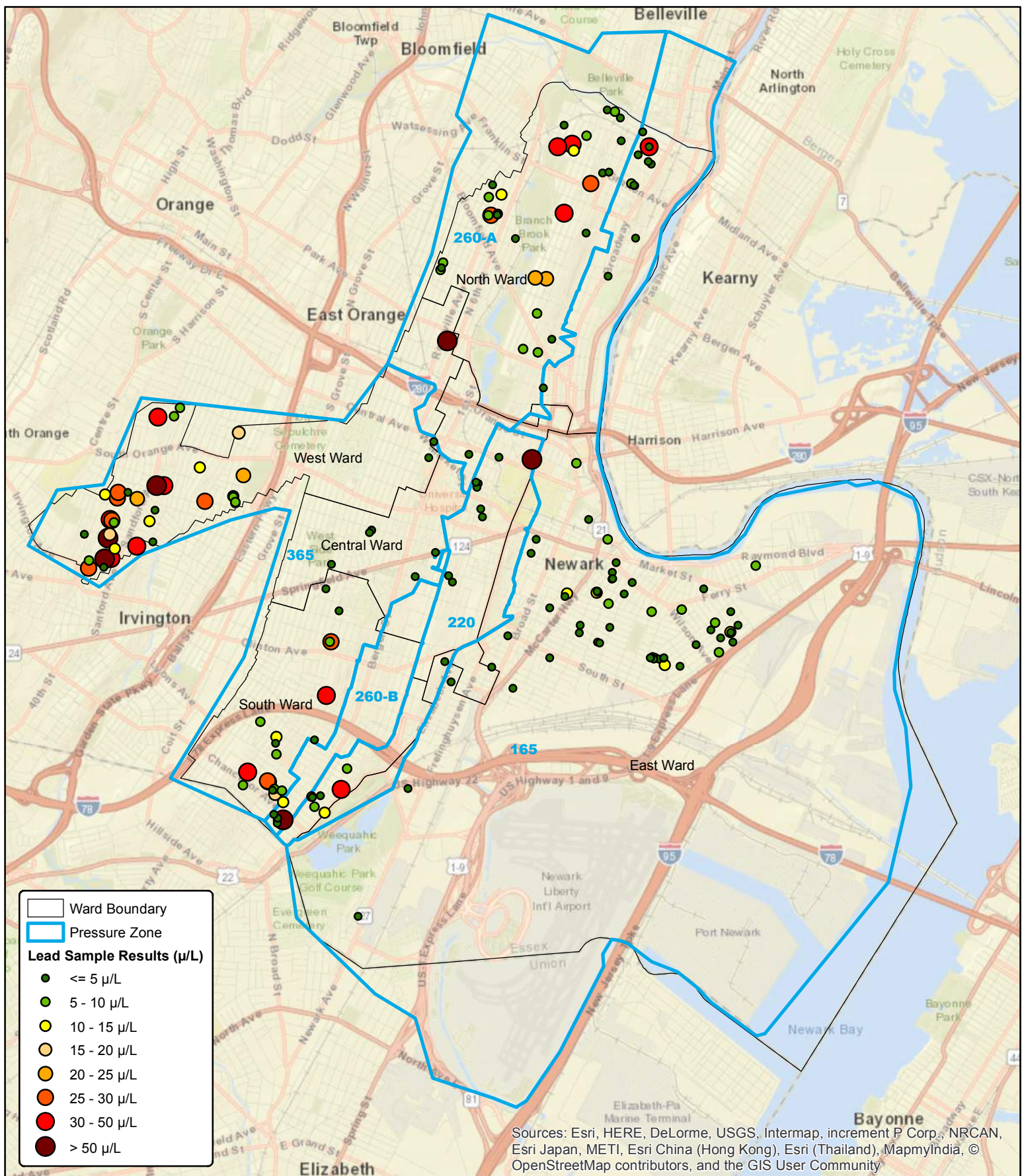
Figure 2-9



Lead Level in the City of Newark

Data Collected: January - June 2017

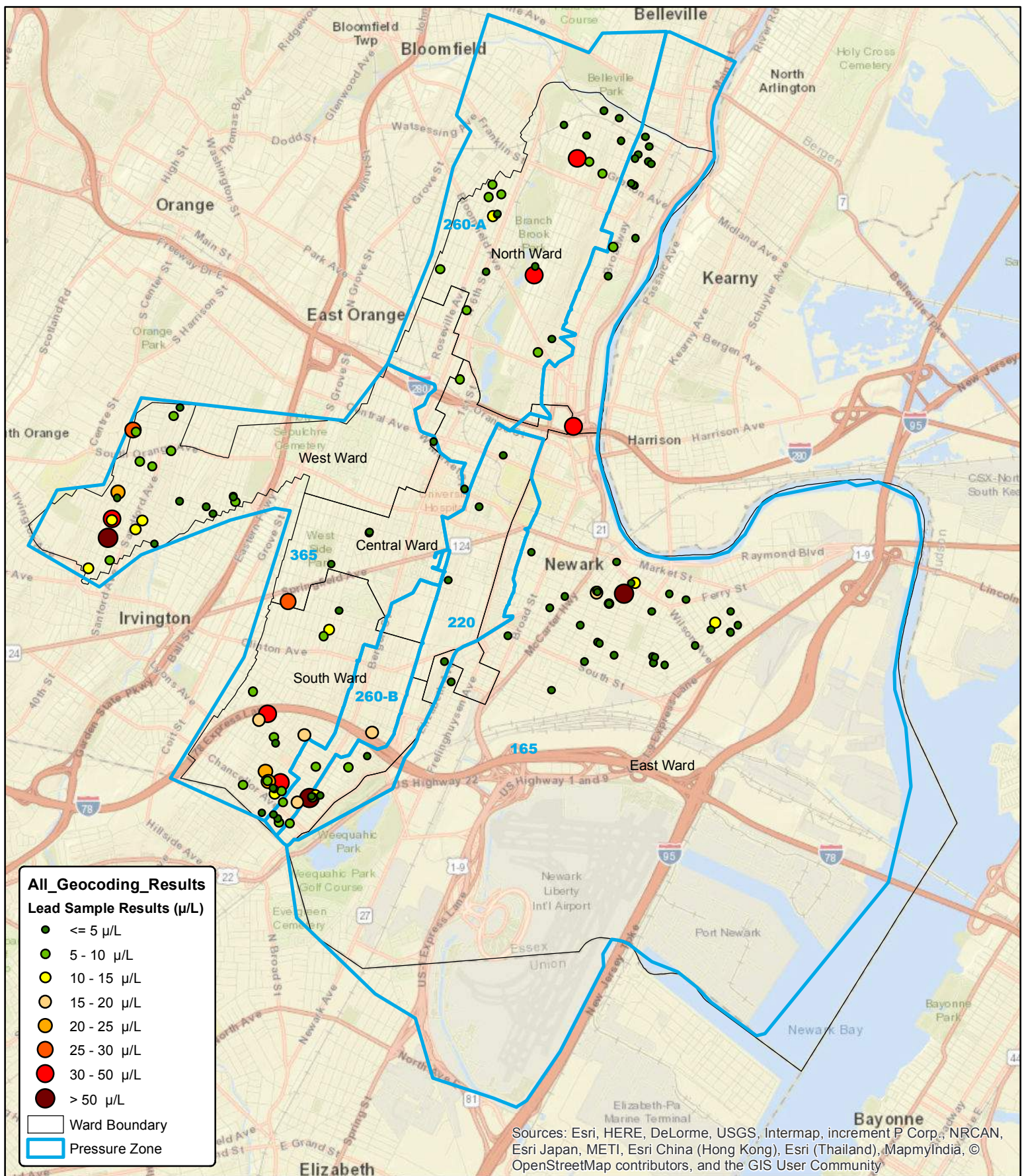
Figure 2-10



Lead Level in the City of Newark

Data Collected: July - December 2017

Figure 2-11



Lead Level in the City of Newark

Data Collected: January - June 2018

Figure 2-12

2.3 Lead Frequency Distribution

A frequency distribution analysis was conducted using multiple rounds of compliance sampling data for both the Pequannock and Wanaque service areas. The analysis was conducted for each service area separately as the service areas receive different CCT as described in Section 2.1. Although regulatory compliance is based on the City of Newark as a whole, the corrosion control chemistry of the two service areas differ. Therefore, the systems were evaluated separately to understand the cause of the high lead levels.

Frequency distributions can provide insight as to whether changes in lead levels may be the result of CCT, sampling variability, or a combination of the two. (Burlingame, 2004) Frequency distributions can assist in establishing the cause of a change in the 90th percentile value and Action Level exceedance. The frequency distribution presented in this Section provides an analysis of the lead sampling results collected since 1992. The data were sorted into several “bins” and percentile categories by lead concentration. The three “bins” that provide the best indication of whether or not CCT has been optimized are: (1) percent less than or equal to 5 µg/L, (2) 50th (median) percentile (µg/L), and (3) percent greater than 15 µg/L and less than or equal to 25 µg/L. Overall trends are also revealed by the frequency distribution data.

2.3.1 Lead Frequency Distribution – Pequannock Service Area

For the Pequannock service area, the frequency distribution analysis was conducted for compliance sampling data collected in 1992, 1998, 2003, 2006, 2012, 2015, the two sampling periods in 2017, and the first period in 2018. Lead sampling rounds were also conducted by the City of Newark in 2002 and 2009; however, samples taken during these periods were concentrated in areas outside of the Pequannock service area.

Figure 2-13 provides an overview of the lead sampling compliance data from the nine (9) sampling events for the Pequannock service area for the different “bins” from less than 5 µg/L to greater than 50 µg/L. **Table 2-1** provides a summary of some statistical parameters based on the lead sampling compliance data, and **Table 2-2** provides an interpretation of the findings of the frequency distribution analyses for the Pequannock service area.

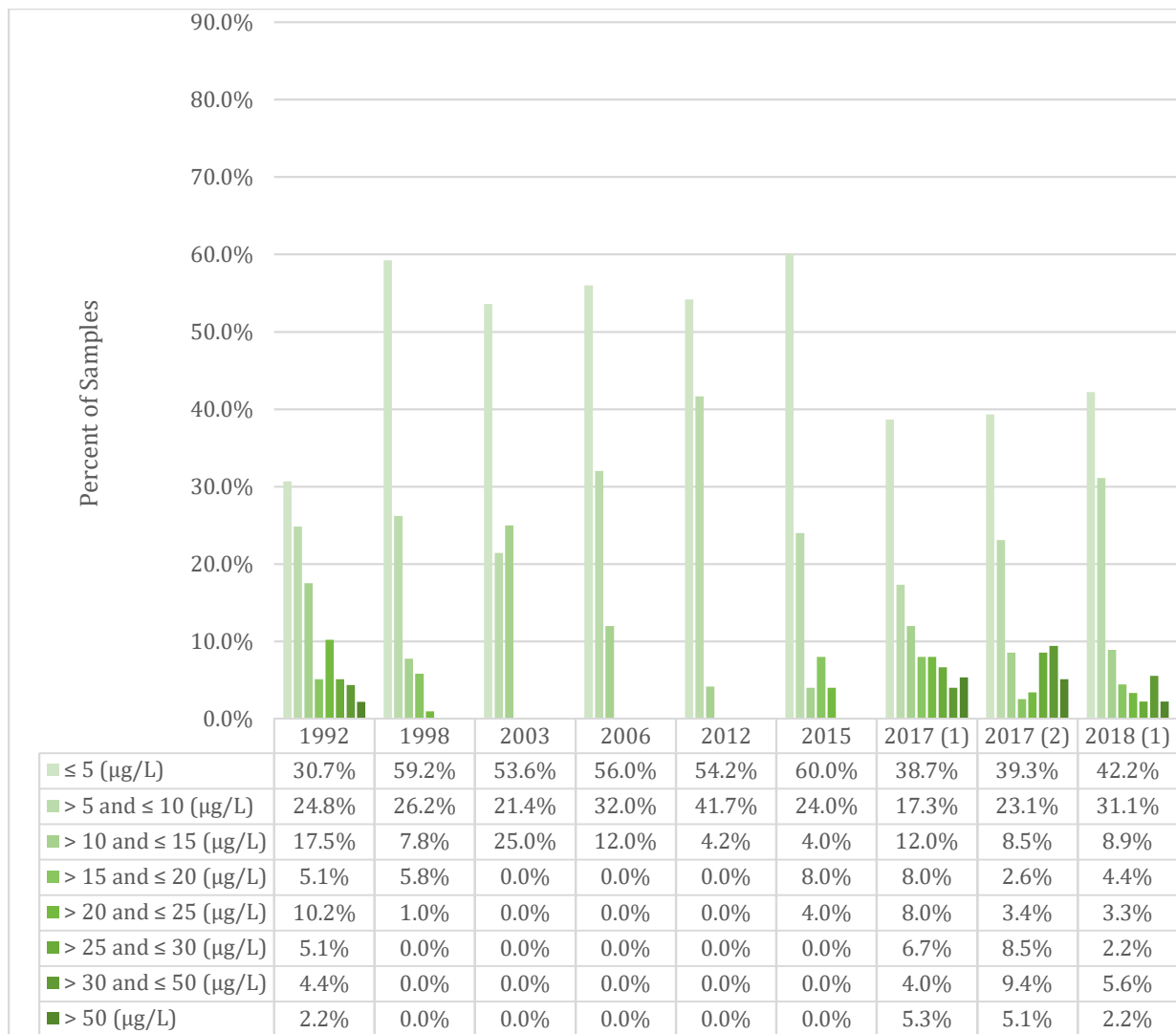


Figure 2-13 – Pequannock Service Area – Lead Sampling Data Percentage Frequency Distribution

Table 2-1 – Summary of Statistical Parameters for Pequannock Lead Sampling Data

Parameter	1992	1998	2003	2006	2012	2015	2017 (1)	2017(2)	2018 (1)
50th Percentile (µg/L)	8.5	4.0	4.8	4.1	5.0	0.0	7.4	7.8	6.4
75th Percentile (µg/L)	16.3	7.4	10.0	7.4	7.3	8.0	17.8	21.2	10.5
90th Percentile (µg/L)	26.8	12.3	12.2	9.5	9.7	15.8	29.8	36.0	22.9
Number of Samples (n)	137	103	28	25	24	25	75	117	90
Number of Samples >15 µg/L (n)	37	7	0	0	0	3	24	34	16
Percent > 15 & ≤ 25 µg/L	15.3%	6.8%	0.0%	0.0%	0.0%	12.0%	16.0%	6.0%	7.8%
Maximum (µg/L)	60.4	23.0	14.2	11.5	14.0	25.0	137.0	77.7	58.9

Table 2-2 – Pequannock Service Area Frequency Distribution Analysis

Data Category/Bin	What does it tell us?	Newark Pequannock Pb Results
Overall frequency distribution	Gives a comprehensive picture of sampling results and allows for comparisons over different periods of time.	The Pequannock WTP implemented sodium silicate chemical addition for CCT in 1997. The lead results from 1998 through 2012 reflect effective control of lead release. However, starting in 2015, lead levels returned to and, in some cases, exceeded 1992 levels. This points to a significant change in system behavior around 2015.
Less than or equal to 5 µg/L	Typically, optimization of a corrosion control treatment is signified by an increased percentage of values that are less than 5 µg/L. When water is treated to be less corrosive, or chemistry is modified to create a stable and insoluble lead compound, overall lead levels will decrease, thereby increasing the percentage of samples with the lowest lead concentrations.	The percentage of samples less than or equal to 5 µg/L increased after CCT was implemented (1997). However, this category only saw 60% of the samples at best, compared to optimized systems which typically see well above 80% of samples less than 5 µg/L. In 2017, the number of samples less than 5 µg/L decreased significantly from 50-60% to about 40%.
50th percentile (µg/L)	The nature of the 90th percentile Action Level is such that it only takes a few samples to greatly affect the outcome of a monitoring period. One seemingly benign deviation in the sampling protocol can greatly skew the 90th percentile value. The 50th percentile is much more resilient and, as such, is a good indicator of the relative effectiveness of a CCT.	The 50 th percentile value decreased from 1992 levels by about half after CCT was implemented in 1997. However, the 50 th percentile nearly doubled in 2017.
Greater than 15 µg/L and less than or equal to 25 µg/L	A small deviation within the 15 to 25 ppb range of samples above could put a system out of compliance. By improving the CCT, a system can provide a greater buffer between the 90th percentile values and the AL of 15 ppb, so as to lessen the effects of an unrepresentative sample.	Prior to implementation of CCT (1992), a significant percentage (15%) of the samples were in this range. After many years of no results being in this range, an uptick in results between 15 and 25 ppb began in 2015, continuing to the first half of 2017; and were still elevated thereafter but slightly less than between 2015 and the first half of 2017. This may be indicative that the most significant impact to the pipe scales may have peaked by early 2017, but this cannot be confirmed.

2.3.2 Lead Frequency Distribution – Wanaque Service Area

A frequency distribution analysis was conducted for compliance sampling data collected in 1992, 2002, 2009, 2012, 2015, the two sampling periods in 2017, and the first period in 2018 for the Wanaque service area. Lead sampling rounds were also conducted by the City of Newark in 1998 and 2003; however, samples taken during these periods were concentrated in areas outside of the Wanaque service area.

Figure 2-14 provides an overview of the lead sampling compliance data from the eight (8) sampling events for the Wanaque service area for the different “bins” from less than 5 µg/L to greater than 50 µg/L. **Table 2-3** provides a summary of some statistical parameters based on the lead sampling compliance data, and **Table 2-4** provides an interpretation of the findings of the frequency distribution analyses for the Wanaque service area.

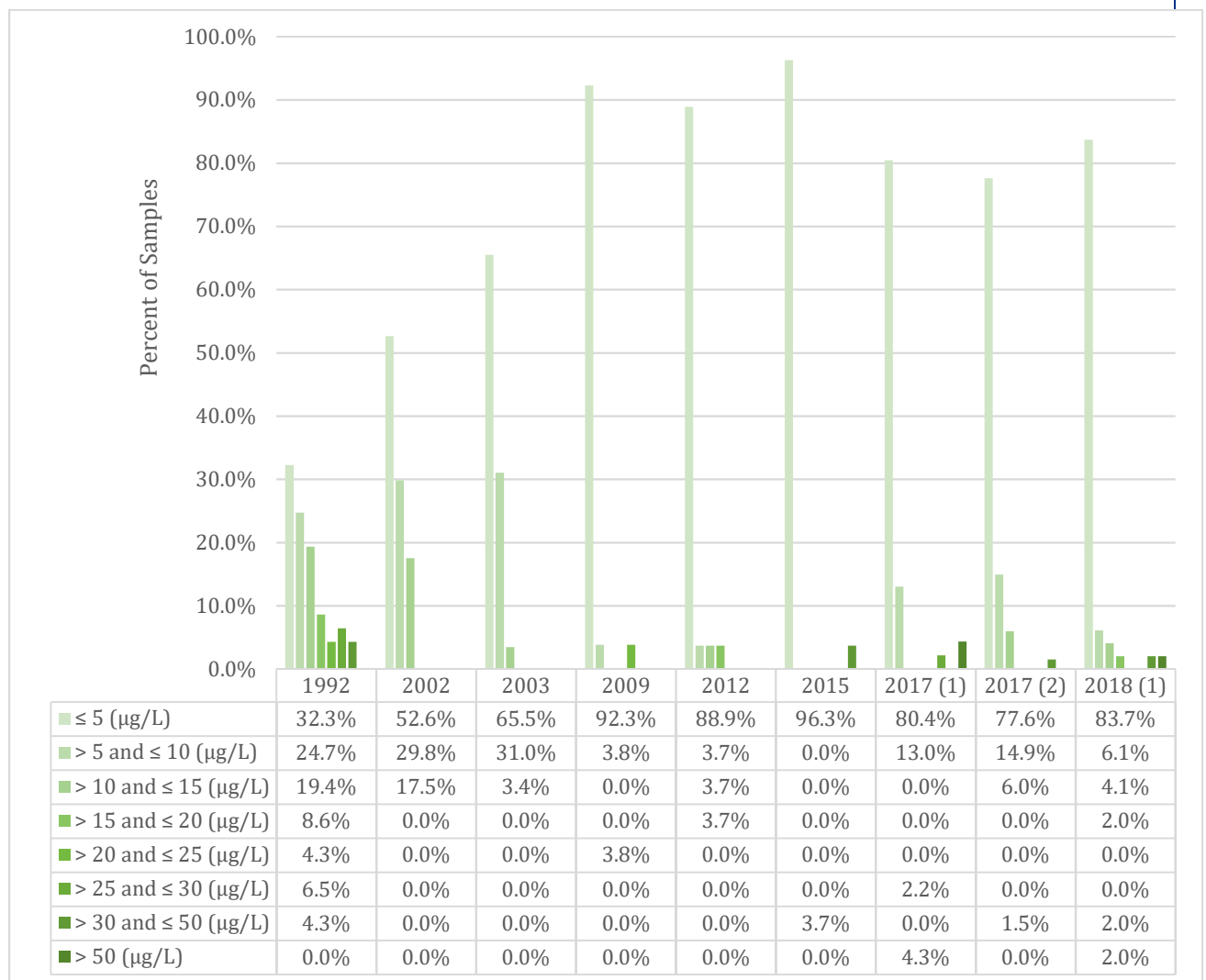


Figure 2-14 – Wanaque Service Area – Lead Sampling Data Percentage Frequency Distribution

Table 2-3 – Summary of Statistical Parameters for Wanaque Lead Sampling Data

Parameter	1992	2002	2003	2009	2012	2015	2017 (1)	2017 (2)	2018 (2)
50th Percentile (µg/L)	6.6	4.6	3.3	0.0	0.0	0.0	0.0	0.0	0.0
75th Percentile(µg/L)	14.2	9.0	6.5	0.0	0.0	0.0	0.0	0.0	0.0
90th Percentile (µg/L)	25.7	11.2	8.4	0.0	6.2	2.0	7.4	8.7	8.7
Number of Samples (n)	93	114	29	26	27	27	46	67	49
Number of Samples >15 µg/L (n)	22	0	0	1	1	1	3	1	3
Percent > 15 & ≤ 25 µg/L	12.9%	0.0%	0.0%	3.8%	3.7%	0.0%	0.0%	0.0%	2.0%
Maximum (µg/L)	49.4	14.9	12.3	24.6	19.0	37.0	84.0	46.1	182.0

Table 2-4 – Wanaque Service Area Frequency Distribution Analysis

Data Category/Bin	What does it tell us?	Newark Wanaque_Pb Results
Overall frequency distribution	Gives a comprehensive picture of sampling results and allows for comparisons over different periods of time.	The Wanaque WTP implemented zinc orthophosphate chemical addition for CCT treatment in the mid 1990s. Between 1992 and 2018, lead sampling results for the Wanaque service area shifted in multiple “bins” (ranges). The 1992 sampling was prior to the CCT treatment improvements. These results point to CCT effectiveness as the cause of a significant decrease in action level beginning in the early 2000s and a shift in the percentage of results into lower bins.
Less than or equal to 5 µg/L	Typically, optimization of a corrosion control treatment is signified by an increased percentage of values that are less than 5 µg/L. When water is treated to be less corrosive, or chemistry is modified to create a stable and insoluble lead compound, overall lead levels will decrease, thereby increasing the percentage of samples with the lowest lead concentrations.	Between 1992 and 2017, there was a large increase in % of samples in this category. Where 1992 saw 32% of samples in this category, 2017 and 2018 sampling saw an increase to an average of 80% between the three sampling pools for lead results less than or equal to 5 ppb. This can again be tied to CCT treatment of zinc orthophosphate. Typically, optimized systems have a majority of sample results (>80%) in the category of <5 ppb.
50th percentile (µg/L)	The nature of the 90th percentile Action Level is such that it only takes a few samples to greatly affect the outcome of a monitoring period. One seemingly benign deviation in the sampling protocol can greatly skew the 90th percentile value. The 50th percentile is much more resilient and, as such, is a good indicator of the relative effectiveness of a CCT.	The 50 th percentile value decreased from 6.6 in 1992 to zero (0) in 2009, and remaining as such ever since indicating effectiveness of the zinc orthophosphate CCT treatment.

Data Category/Bin	What does it tell us?	Newark Wanaque_Pb Results
Greater than 15 µg/L and less than or equal to 25 µg/L	A small deviation within the 15 to 25 µg/L range could put a system out of compliance. By improving the CCT, a system can provide a greater buffer between the 90th percentile values and the AL of 15 µg/L, so as to lessen the effects of an unrepresentative sample.	There was a large decrease in the number of results in this category after the initial sampling round in 1992, which was prior to implementation of CCT. In 2009 and 2012, there was a slight increase in result in this category, which could indicate sampling variability but not definitively. Overall, occurrences of lead levels above the action level decreased significantly indicating the effectiveness of the CCT treatment.

2.3.3 Pequannock Service Area Focus

When separating the LCR compliance sampling data for the Pequannock and Wanaque Gradients, it is clear from the results of the individual lead frequency distribution analyses that a large majority of the lead exceedances have occurred in the Pequannock service area. The frequency of lead exceedances in Pequannock alone has triggered the Lead Action Level exceedances for the City of Newark since the first half of 2017. If the Pequannock and Wanaque Gradients were regulated independently, the Wanaque service area would have been in compliance with the LCR from 2002 to present with 90th percentile values ranging from 0.0 to 11.2 µg/L over that period. Over that same period, the Pequannock 90th percentile values ranged from 9.5 to 36.0 µg/L. In the most recent sampling round, the second half of 2018, the Pequannock 90th percentile based on the verified LCR sampling pool was 39.5 µg/L and the Wanaque 90th percentile based on the verified LCR sampling pool was 4.12 µg/L.

The historic LCR compliance sampling data, as well as the data recently collected as part of this study, show that the current CCT for the Wanaque service area is able to consistently reduce lead levels in the drinking water to below the Lead Action Level.

Due to the determination that the Pequannock system is triggering the Lead Action Level exceedances for the City of Newark, the remainder of this report will focus on the Pequannock service area. This report will evaluate the cause of the elevated lead levels and provide recommendations for reducing lead levels in the Pequannock system.

Since, as a whole, the entire City of Newark is not currently meeting the lead action level due to the Pequannock/Wanaque combined reporting, a more detailed report was requested by NJDEP providing further analysis on the Wanaque Gradient, including sequential sampling and pipe scale analyses. The analysis and any recommendations to optimize CCT in the Wanaque Gradient will be presented in a separate report.

Section 3

Historic Water Quality and Chemical Usage Data

Historic water quality data was obtained from multiple sources provided by NJDEP Drinking Water Watch (as of September 21, 2018), as well as from the City of Newark. The data used for this analysis includes the following:

- City of Newark – Raw Water Supply Quality Analysis for 2016 and 2017. This included monthly averages of pH, temperature, turbidity, color, calcium, alkalinity, hardness and conductivity.
- Optimal Corrosion Control Treatment Recommendations report, prepared by the City of Newark, December 2017.
- Comprehensive Technical Assistance (CTA) Report, prepared by H2M, May 2016.
- Comprehensive Performance Evaluation Pequannock Water Treatment Plant Report, prepared by Aquamize, July 2014.
- Disinfection By-Product Control Bench Scale Investigation, prepared by Carollo Engineers, May 2016
- Daily analysis sheets recorded at the Pequannock WTP lab for delivered and raw water from 2015-2018 (excluding January – October 2017, but including July 2nd, 3rd and 4th of 2017) provided by the City of Newark. This included pH, temperature, chlorine residual, turbidity, color, calcium, alkalinity, hardness and conductivity for delivered water (system point-of-entry (POE)) and pH, temperature, turbidity, color, calcium, alkalinity, hardness and conductivity for the raw water.
- Pequannock WTP monthly chemical usage for 2016 (excluding November), as well as January – March of 2018 provided by the City of Newark. This includes Clarion (potassium aluminum), lime, sodium silicate, chlorine (pre and post) and PACl as minimum, maximum and average dosages in mg/L, as well as total amounts used in pounds per day (lbs/day).
- Monthly averages for raw and delivered water (system POE) data, as well as chemical dosage data, for 2016 and 2017. This includes the turbidity and alkalinity for raw water and the average pH and chlorine residual for delivered water. The monthly average chemical dosage data was provided for Clarion (potassium aluminum), PACl, silicate, chlorine and polymer in mg/L, and lime in lbs/day.
- Total organic carbon (TOC) monthly data for raw and delivered water (recorded from Test House), provided by the City of Newark. This includes October of 2014, May – August and October of 2016, all of 2017 and January – April of 2018 for raw water. January – March, May, November and December of 2017 as well as February and April of 2018 data, were provided for delivered water.

- Pequannock WTP annual average chemical dosing for 2014 provided by the City of Newark.
- Delivered water (system POE) monthly averages for 2016, 2017 and January-March of 2018, provided by the City of Newark. This includes sulfate, magnesium and total dissolved solids (TDS).
- Chemical dosing 2017 monthly chemical usage (lbs), yearly total usage and yearly average, provided by the City of Newark. This includes alum/polymer, chlorine, PACl, lime, polymer and silicate.
- Raw water and delivered water (system POE) monthly turbidity averages for 2017, provided by the City of Newark.
- Raw water and delivered water (system POE) data , as well as chemical dosage data, for the first half of September 2018, provided by the City of Newark. This included average pH, temperature, alkalinity and calcium for raw water, and pH, temperature, chlorine residual, alkalinity and calcium sampled at Test House.
- Source Water Monitoring Program data, provided by the City of Newark for September 2015, March, April, May, June and September of 2016, and April of 2017. This included a sample from each month for temperature, dissolved oxygen (DO), pH, conductivity, color, turbidity, alkalinity, hardness and TOC.
- Data from NJDEP Water Watch which was mainly used to fill in gaps in the City of Newark's data for raw and delivered water (system POE), when available. In addition, NJDEP Water Watch was used to collect data at the other sampling sites, such as the Cedar Grove Reservoir, Valley Road, Belleville Reservoir and the distribution system.
- Valley Road Rechlorination Station daily chlorine residual and pH from 2005 to September 2018, and a few data points prior to 2005.

3.1 Recent Water Quality Data

Recent data obtained from Newark and NJDEP's Water Watch were used for the purpose of understanding the source and finished water characteristics of the Pequannock WTP as related to corrosion control. The data used are summarized in **Table 3-1**.

Table 3-1 – Key Water Quality Parameters for Corrosion Control Evaluation

Parameter	Water Type	Duration	Frequency
Temperature	Source/Finished	January 2015 – April 2018	Daily, excluding January – October 2017
pH	Source/Finished/ Valley Road Rechlorination Point-of-Entry (POE)	January 2015 – August 2018 (used for current averages) February 1992 – August 2018 (used for historic trends) Valley Road: January 2005 to August 2018 (used for distribution system POE)	2015-2018: Daily, excluding January – October 2017, bi- weekly after April 2018 for delivered water (POE) 2005-2018 historic: a few samples per year; sporadic Valley Road: daily
Alkalinity	Source/Finished	January 2015 – August 2018	Daily, excluding January – October 2017, bi-weekly after April 2018 for delivered water (POE)
Calcium	Source	January 2015 – April 2018	Daily, excluding January – October 2017
Chlorine Residual	Valley Road Rechlorination – Post-Chlorine POE	Valley Road: January 2005 to August 2018	Daily
Magnesium	Source	January 2016 – February 2018	Monthly averages, excluding September 2016
Total Dissolved Solids	Source	January 2016 – March 2018	Monthly averages
Chloride	Source	June 1994 – October 2017	16 samples
Silica	Finished	June 2009 – August 2018	5 samples in 2009, bi weekly starting July 2016
Sulfate	Finished	June 1994 – March 2018	22 samples from NJDEP Water Watch, monthly averages from the City of Newark for January 2016 – February 2018 (excluding September 2016)

Because water systems experience variability in water quality throughout the year, as would be expected with a northeast reservoir supply, it is important to evaluate the full range of water quality expected. Four (4) seasonal scenarios were developed based on seasonal water quality fluctuations in the Pequannock Reservoir source water. The seasonal scenarios are as follows:

- Warm temperature conditions(June 19th – September 18th) – Summer
- Cooling period (September 19th – December 18th) – Fall
- Cold temperature conditions (December 19th – March 18th) – Winter
- Warming Period (March 19th – June 18th) – Spring

Figures 3-1 through 3-10 illustrate source and delivered water quality (where available), as well as seasonal trends, for temperature, pH, alkalinity, calcium, and magnesium. **Figure 3-11**

provides the amount of silica residual present in the delivered water in comparison to the amount of sodium silicate being dosed into the water, in mg/L as SiO₂. **Figure 3-12** presents the delivered water levels of chloride and sulfate from the available data. As evident from the figures, daily data from January through October 2017 are missing from Newark's records for alkalinity and calcium. The following remarks on data analysis are noted:

- The seasonal variability in source water temperature is evident, as color-coded and labeled in **Figures 3-1** and **3-2**. The source water temperature, over the last four years, from 2015 to 2018, generally ranged from 5 degrees Celsius in winter to 25 degrees Celsius in the summer.
- Source water pH ranges from 5.7 to 7.5 as shown in orange in **Figure 3-3**. Finished water pH leaving the Pequannock WTP over the last four years, from 2015 to 2018, has shown variability ranging from 6.0 to 8.8, as shown in blue. Over the last 2 years, finished water pH has tended to range from 6.5-7.5. Longer term pH trends are described in Section 3.3.1.
- Alkalinity in the source water generally ranged between 10 and 35 mg/L as CaCO₃ over the last four years, from 2015 to 2018, as shown in **Figures 3-5** and **3-6**, depending on the season. Alkalinity increases as the water temperature increases and decreases as the water cools.
- Calcium levels in the source water have a generally increasing trend from the cold to warm seasons, as shown in **Figures 3-7** and **3-8**. Calcium concentrations in the source water are generally between 6 and 14 mg/L as Ca²⁺ and increase in the finished water to between 10 and 18 mg/L as Ca⁺, due to the addition of lime.
- Magnesium in the delivered water ranged from 3.8 mg/L as Mg to 5 mg/L as Mg as shown in **Figures 3-9** and **3-10**. No obvious seasonal trends are present. The raw magnesium levels are assumed to be similar to the levels in the delivered water, as no chemicals with significant amounts of magnesium are added at the plant.
- Silica concentrations measured at the plant finished water (Test House) ranged from 5.7 to 12.0 mg/L as SiO₂ between December 2015 and August 2018 as shown in **Figure 3-11**. The sodium silicate dosed at the Pequannock WTP ranged from 10.1 – 14.1 mg/L as sodium silicate, or 2.9 to 4.1 mg/L as SiO₂. It is reported that the silica concentration in the raw water is approximately 4.0 mg/L as SiO₂ (Newark, 1994).
- Chloride in the delivered water ranged from 25 mg/L as Cl to 45 mg/L as Cl from 1994 to 2017 as shown in **Figure 3-12**. Polyaluminum chloride (PACl) is added at the Pequannock WTP for coagulation, which contributes to increased chloride levels. As expected due to runoff from road salts, chloride levels were higher in the winter months than in other seasons. The overall annual average was 33.1 mg/L as Cl.
- Sulfate in the delivered water ranged from 8.1 mg/L as SO₄ to 16.3 mg/L as SO₄²⁻ with an average of 11.4 mg/L as SO₄ as shown in **Figure 3-12**. The Pequannock WTP adds aluminum sulfate (alum) as one of their coagulants, which contributes to the sulfate levels.

Figure 3-1 Historic Pequannock WTP Temperature - Influent and Delivered Water

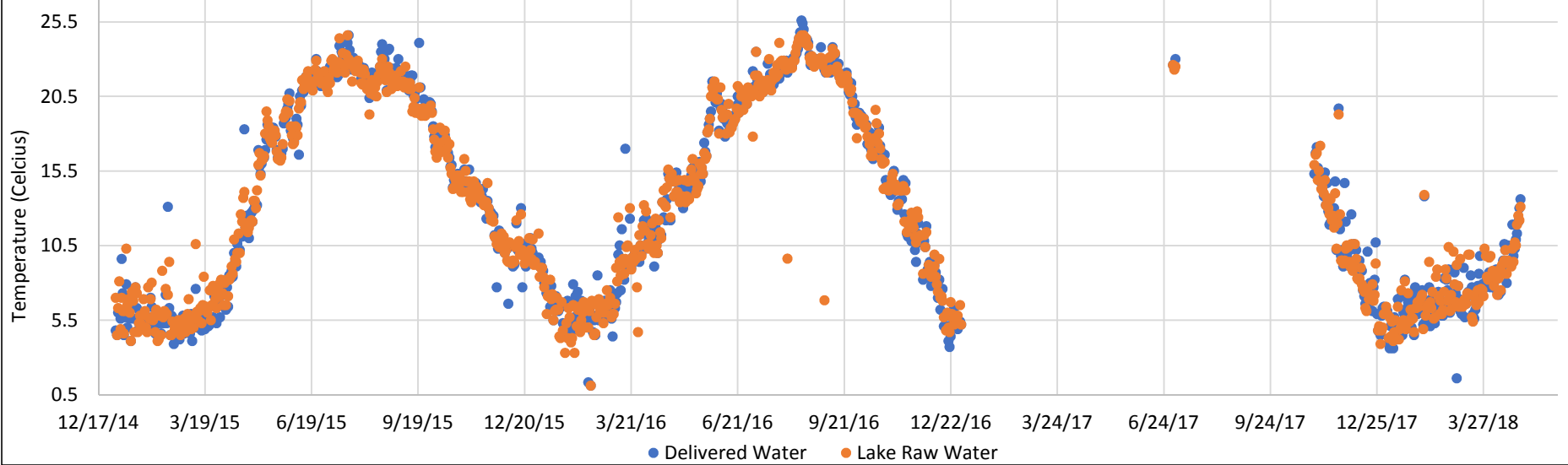


Figure 3-2 Historic Pequannock WTP Temperature - Influent Water Seasonal Trends

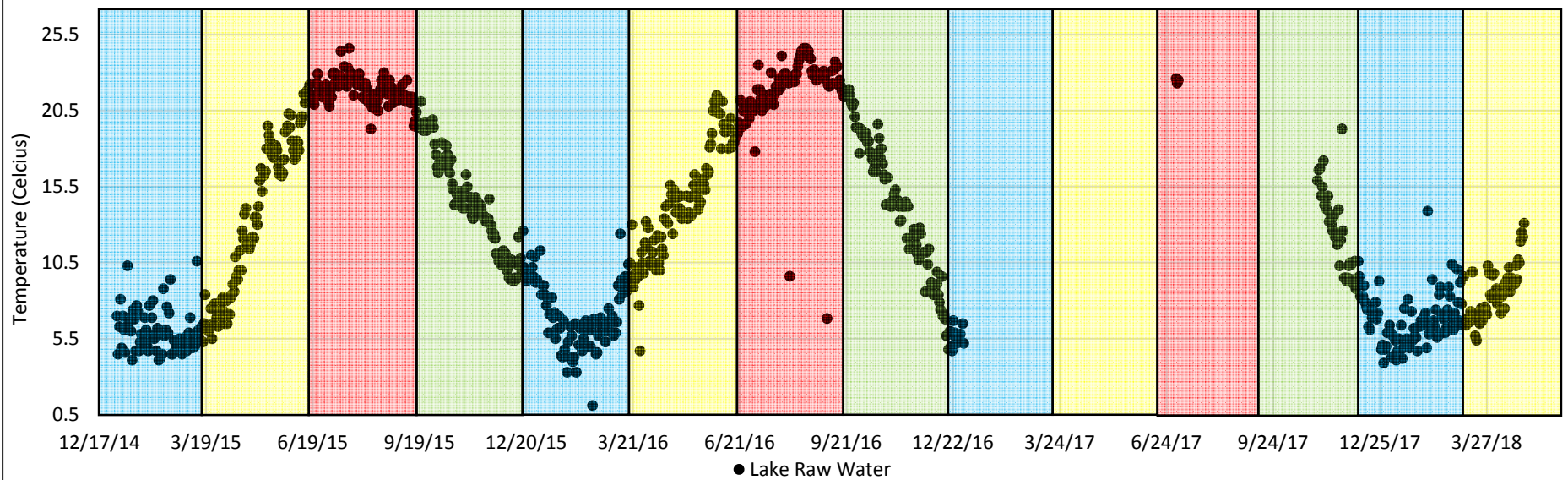


Figure 3-3 - Historic Pequannock WTP pH - Influent and Delivered Water

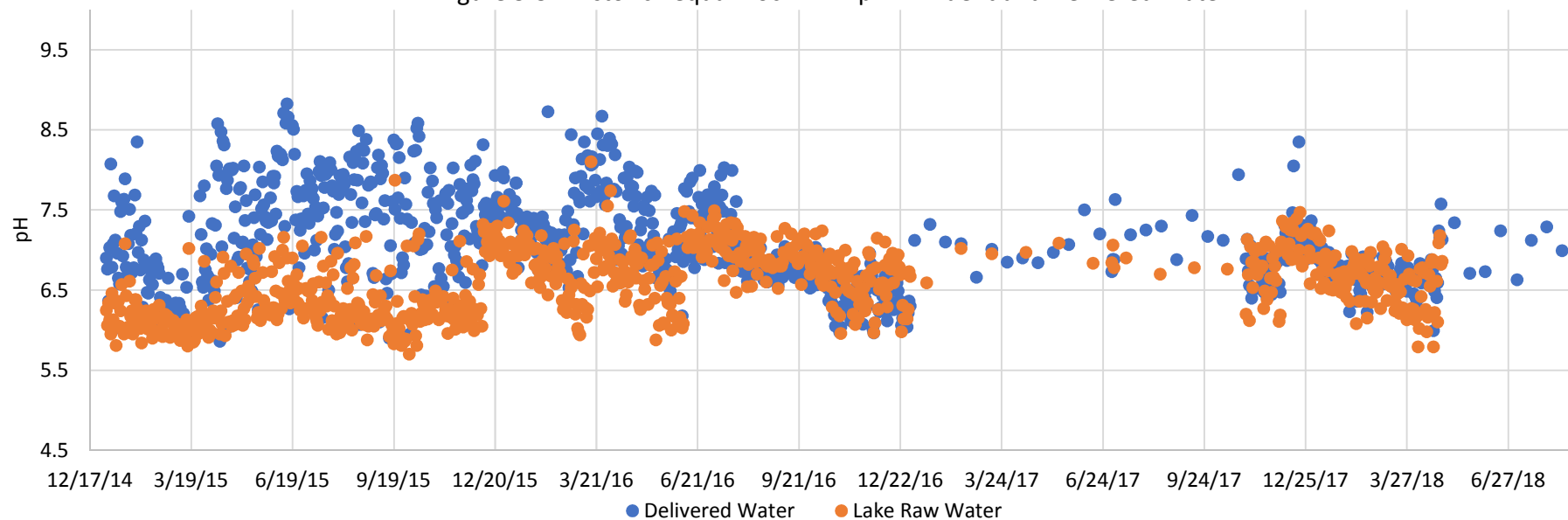


Figure 3-4 - Historic Pequannock WTP pH - Influent Water Seasonal Trends

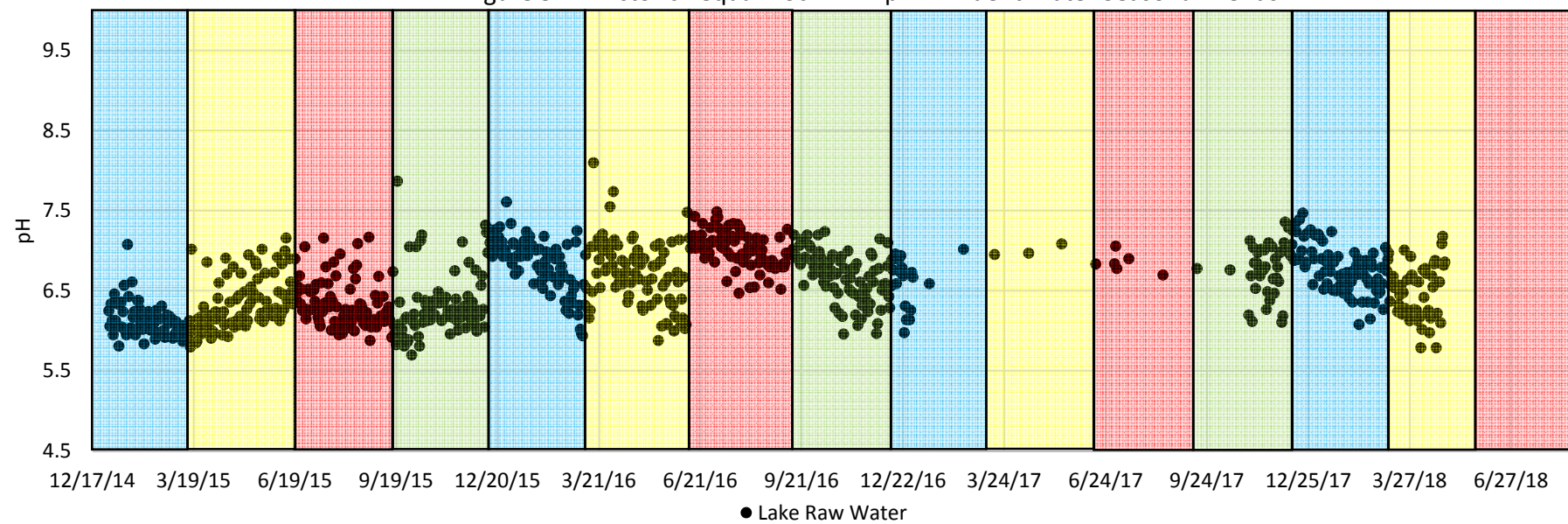


Figure 3-5 - Historic Pequannock WTP Alkalinity - Influent and Delivered Water

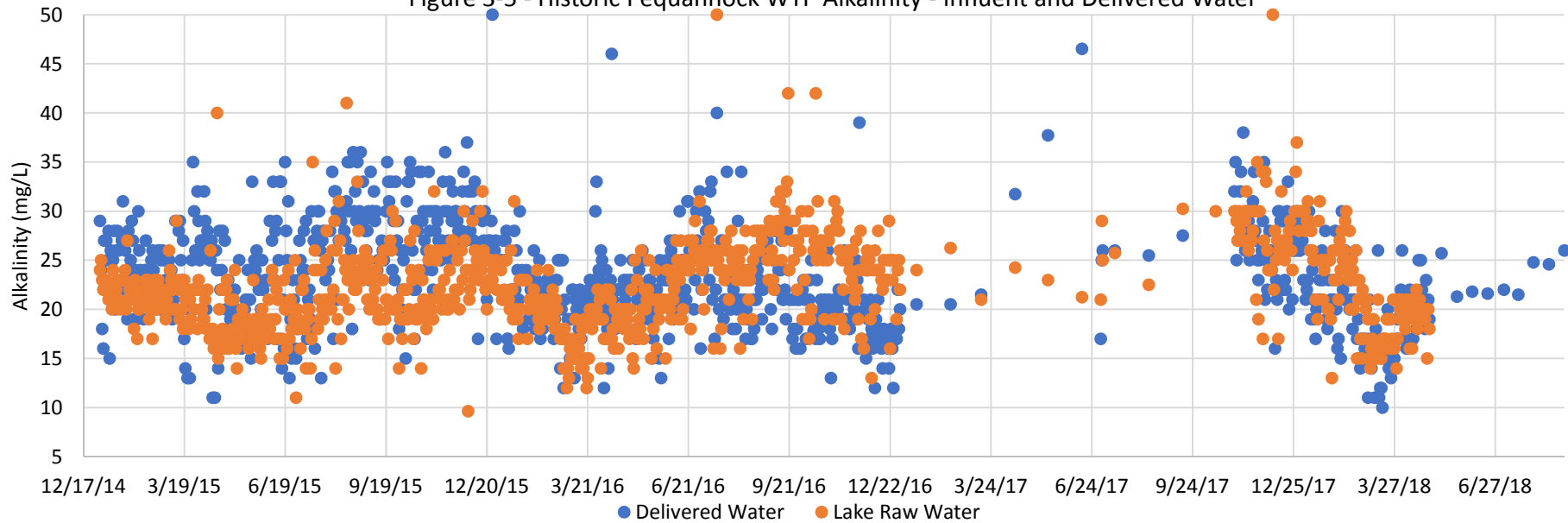


Figure 3-6 - Historic Pequannock WTP Alkalinity - Influent Water Seasonal Trends

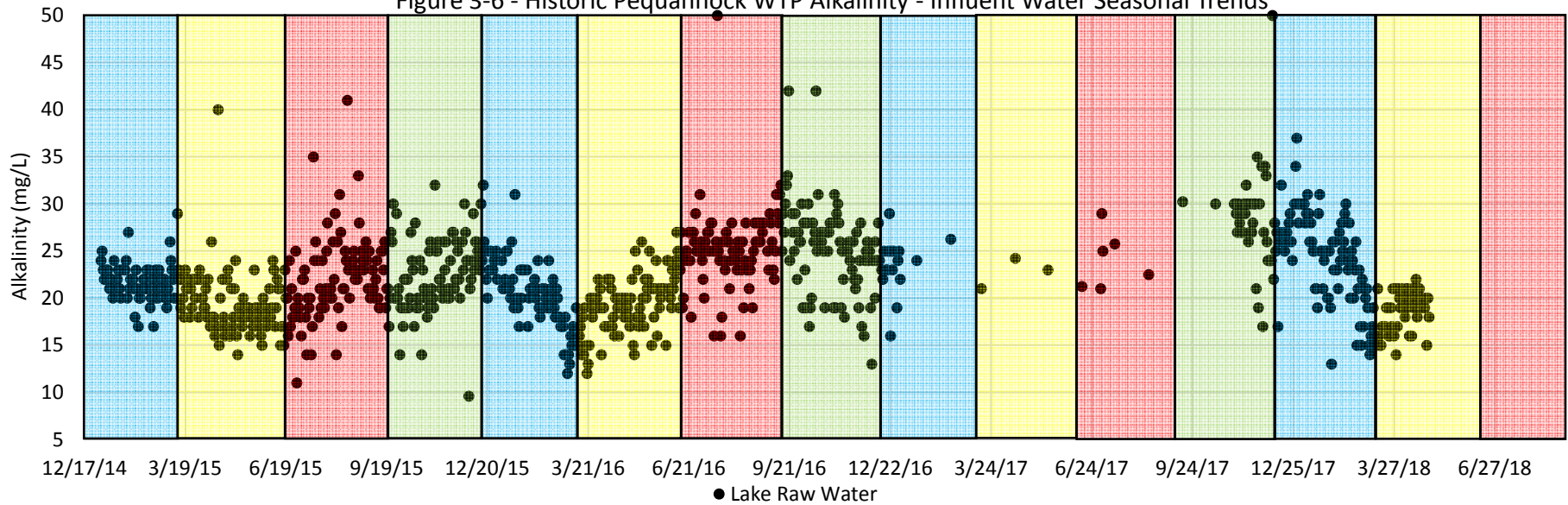


Figure 3-7 - Historic Pequannock WTP Calcium - Influent and Delivered Water

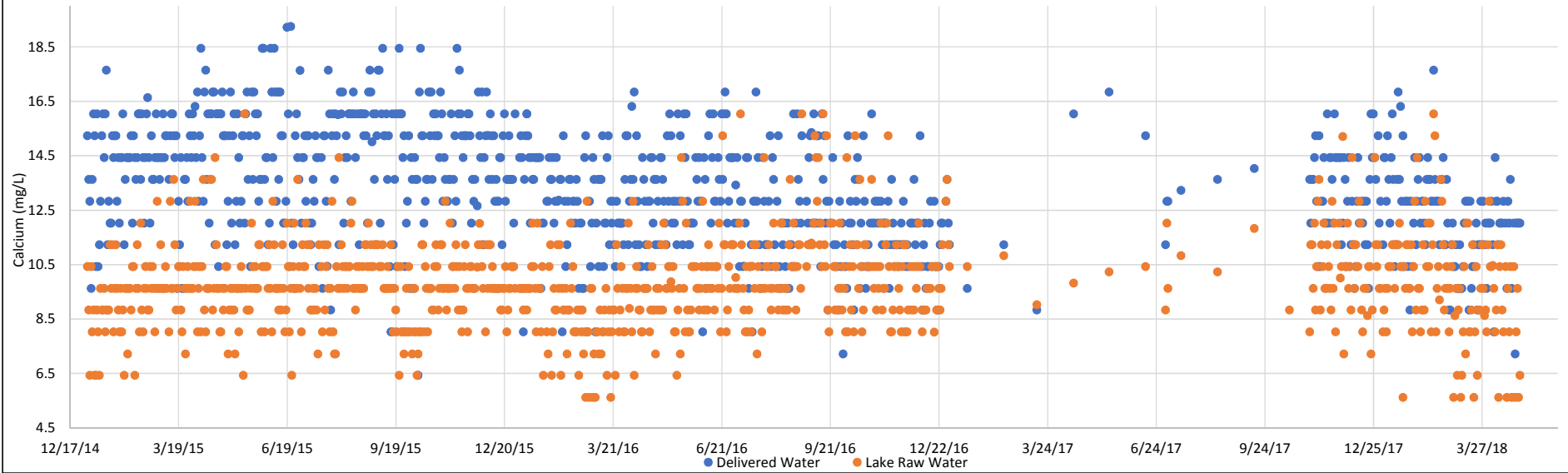


Figure 3-8 - Historic Pequannock WTP Calcium - Influent Water Seasonal Trends

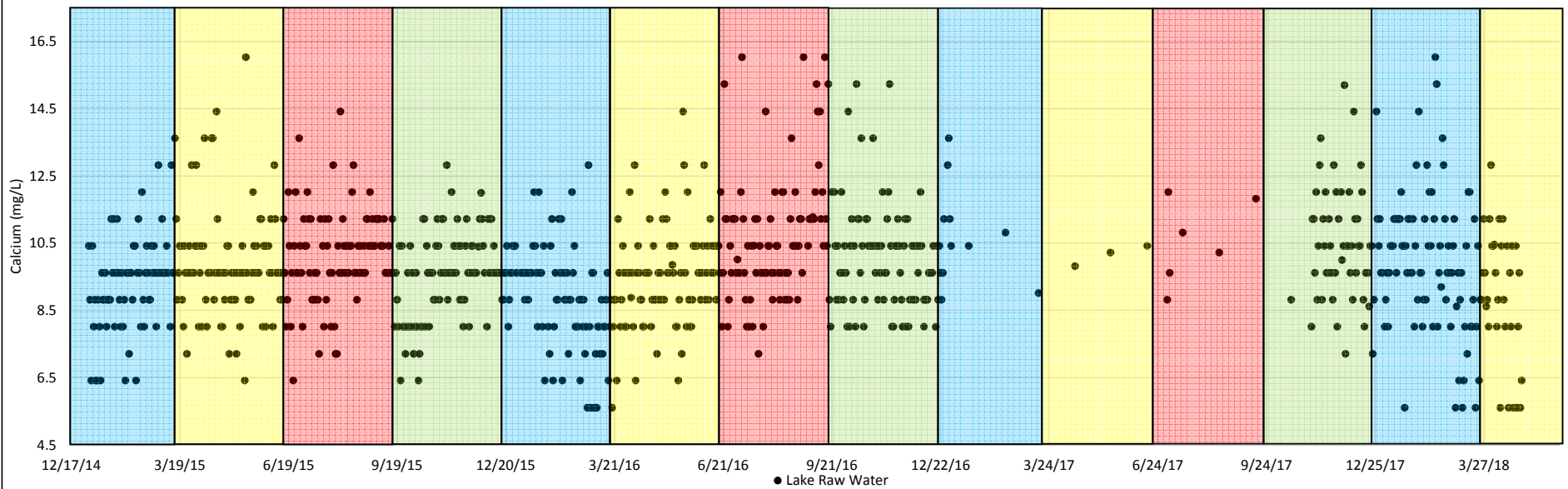


Figure 3-9 - Historic Pequannock WTP Magnesium - Delivered Water

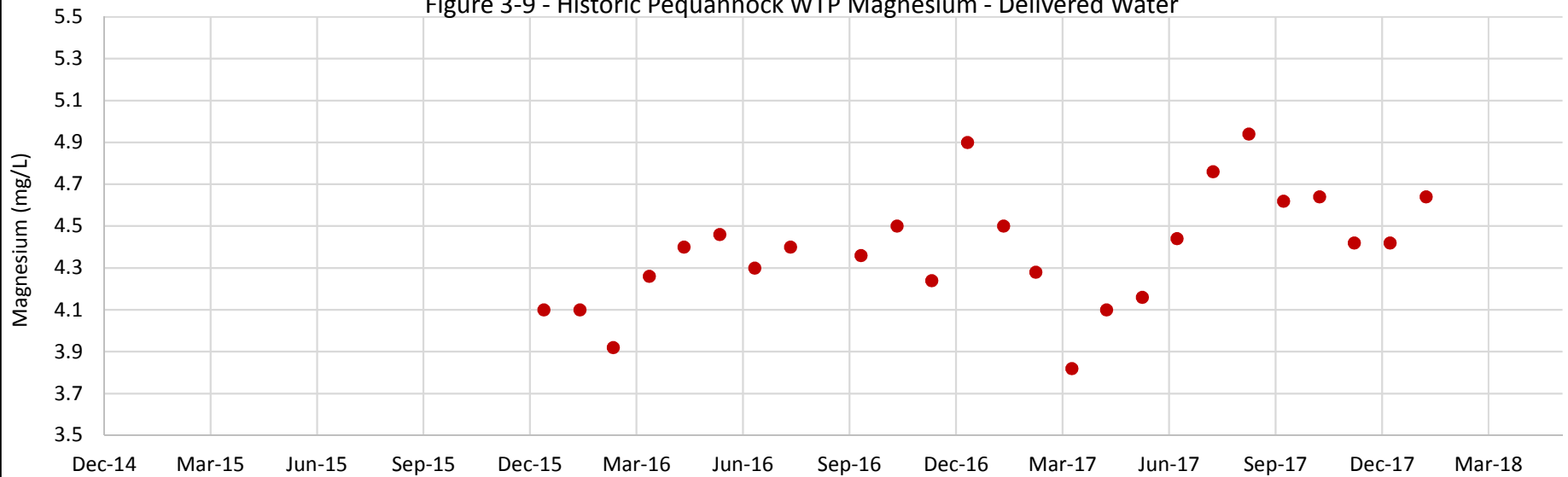
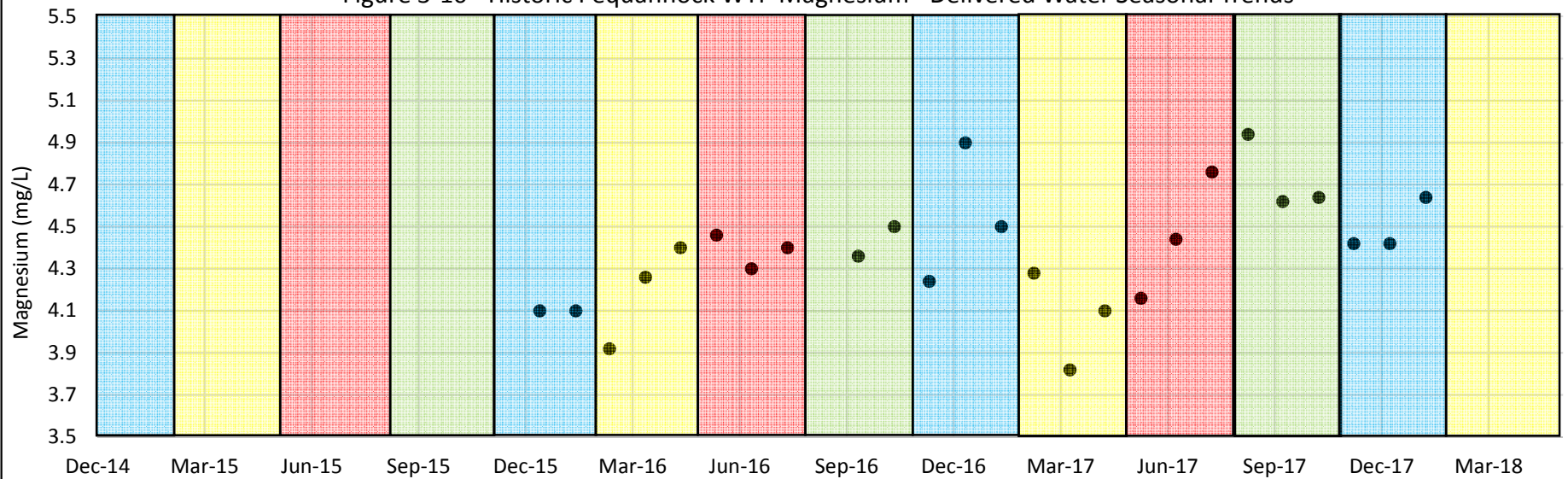


Figure 3-10 - Historic Pequannock WTP Magnesium - Delivered Water Seasonal Trends



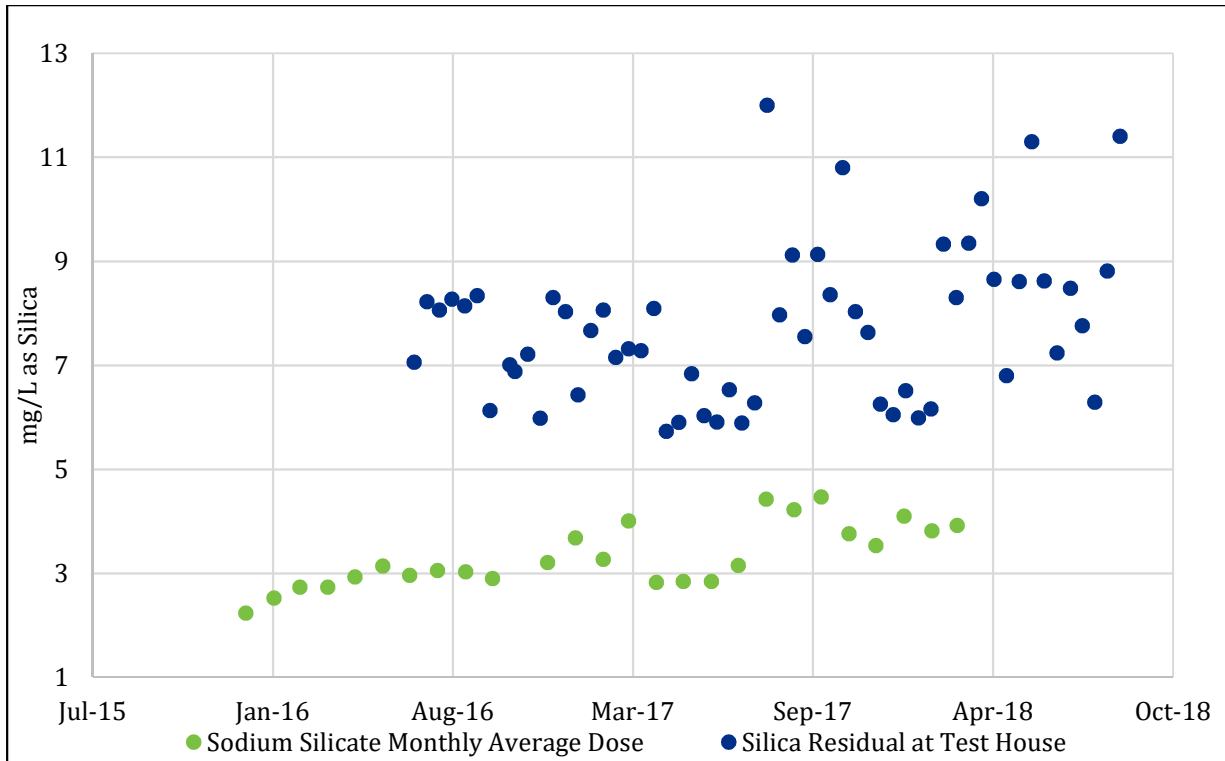


Figure 3-11 – Historic Pequannock WTP Silica – Dose vs. Delivered Water

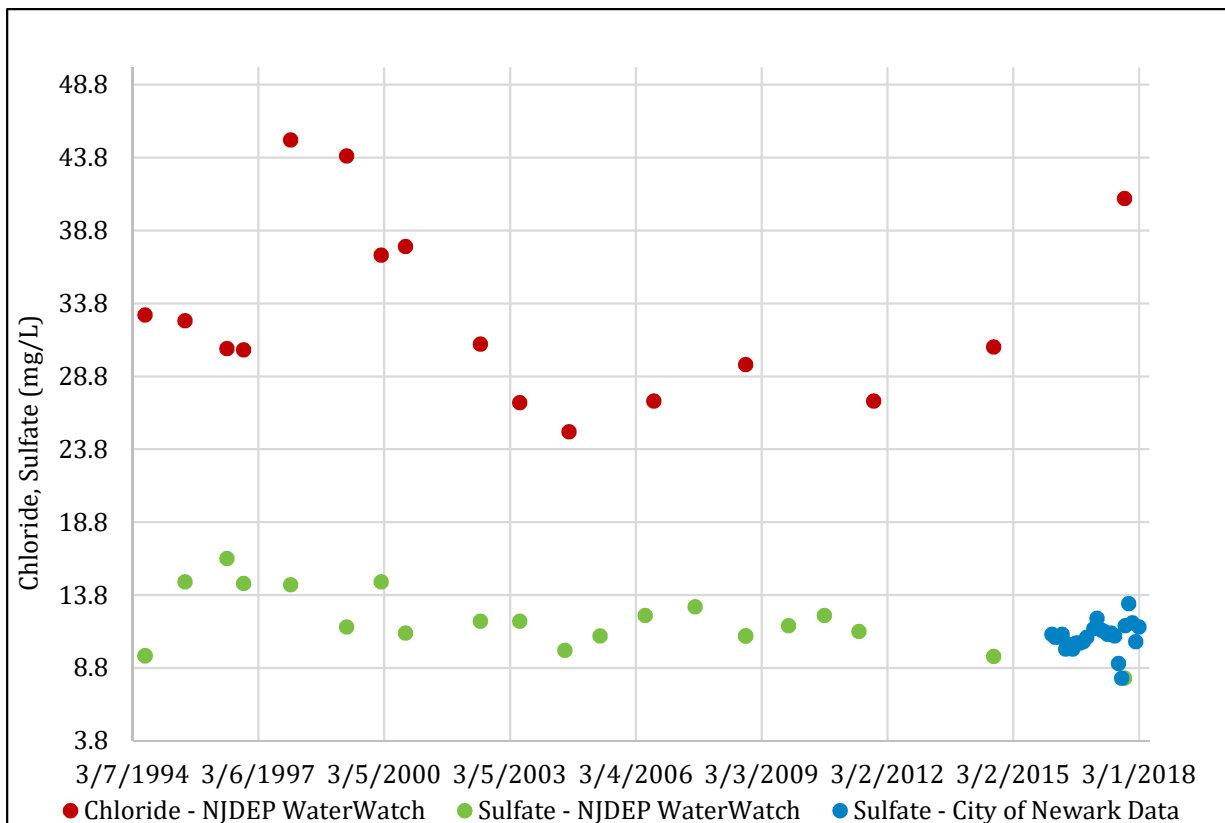


Figure 3-12 – Historic Pequannock WTP Chloride and Sulfate – Delivered Water

3.1.1 Chloride-to-Sulfate Mass Ratio

Galvanic corrosion on lead-copper joints can be accelerated and cause a release of lead with a higher chloride to sulfate mass ratio (CSMR). CSMR is calculated by dividing the average chloride concentration by the average sulfate concentration (Nguyen, Stone, Clark, & Edwards, 2010). The literature reports a “threshold” CSMR value of 0.5, above which galvanic corrosion of lead solder on copper piping can increase. The greatest concerns, however, are utilities with lead solder joints that change their water chemistry to increase CSMR from below 0.5 to above 0.5 as indicated in the Water Research Foundation (WRF) 4088 Study (Nguyen, Stone, Clark, & Edwards, 2010).

The researchers in the WRF study observed that in waters with chloride to sulfate equal to or less than 0.5, very low corrosion rates were observed. High chloride relative to sulfate, yielding CSMRs above 0.5, tended to increase galvanic corrosion of lead solder connected to copper pipe. They also observed, statistically, that as relative concentrations of chloride to sulfate increased in the water supply, the 90th percentile lead concentration generally increased. In their bench-scale experiments, waters with high CSMR were consistently more aggressive in increasing lead leaching from solder galvanically connected to copper.

Based on an average chloride concentration of 33.1 mg/L and an average sulfate ratio of 11.4 mg/L, Newark’s average CSMR is 2.9. Although Newark’s CSMR is above the 0.5 threshold, there are many systems that operate with similar or higher CSMRs that do not have high lead levels or Action Level exceedances. The likely reason for this is that much of the solder exposed to the water may have been released at extremely low rates over decades. The WRF research focused on simulating release of lead from solder that was abruptly subjected to high CSMR water. This is corroborated by full-scale experience where the CSMR changed abruptly due to a process or water quality change (e.g., systems changing from alum to PACl or alum to ferric chloride). In these cases, the “baseline” condition was a relatively low CSMR (often times greater than 0.5), and the operational change caused a sudden increase in CSMR, which contributed to lead release and spikes in tap water sampling results (Nguyen, Stone, Clark, & Edwards, 2010).

Newark doses both alum and PACl as coagulants at their Pequannock WTP and has had a consistent dosing ratio in recent history. The data for chloride and sulfate have shown consistent levels within a narrow range since the beginning of the available data set in 1994, as shown in **Table 3-2**. The galvanic corrosion in lead solder joints on copper piping due to the elevated CSMR in Newark’s system has likely occurred over many years at a slow rate, since no drastic change in the CSMR is apparent in at least the last 24 years.

Table 3-2 – Calculated CSMR Values from Available Chloride and Sulfate Data

Date	Chloride as Cl	Sulfate as SO ₄	Calculated CSMR Value
6/23/1994	33	9.64	3.42
6/6/1995	32.6	14.7	2.22
6/4/1996	30.7	16.3	1.88
10/28/1996	30.6	14.6	2.10
12/12/1997	45	14.5	3.10
4/14/1999	43.9	11.6	3.78
2/7/2000	37.1	14.7	3.31
9/7/2000	37.7	11.2	3.37

Date	Chloride as Cl	Sulfate as SO ₄	Calculated CMSR Value
6/21/2002	31	12	2.58
5/30/2003	27	12	2.25
10/16/2008	29.6	11	2.69
9/11/2014	30.8	9.58	3.22
10/25/2017	41	8.09 ^[1]	5.07 ^[1]

^[1] Sulfate data from October 25, 2017 appears to be an anomaly and too low, resulting in a high apparent CMSR. Additional data will be reviewed to determine if this value is accurate.

3.2 Chemical Usage Observations

Chemical usage data at the Pequannock WTP was obtained from the City of Newark and analyzed for dosage trends that may affect the seasonal water quality variations for pH, alkalinity, calcium, and other corrosion-related parameters as discussed in Section 3.1. The data obtained includes monthly averages from January 2016 – March 2018, excluding 2017, for the following chemicals:

- Clarion – Potassium alum
- Lime (100% Hydrated Lime)
- Sodium Silicate
- Polyaluminum chloride (PACl)
- Chlorine gas

Figures 3-13 and 3-14 show the chemical dosage data for Clarion, lime, sodium silicate, and PACl, and seasonal trends where present. The data was also compared with 2014 data presented in the CTA report. The following remarks on data analysis for chemical usage are noted:

- No significant seasonal variation was observed in Clarion (alum) dosage, which ranged from 8.9 mg/L to 9.9 mg/L. The average dose of the data provided for Clarion was 9.5 mg/L. Generally, the average Clarion dose is consistent throughout the year and consistent with the average dose in 2014 which was 9.2 mg/L.
- No significant seasonal variation was observed in lime dosage, which ranged from 2.6 mg/L to 4.2 mg/L. The average dose of the data provided for lime was 3.1 mg/L. According to the CTA, the average lime dose in 2014 was 4.5 mg/L.
- No significant seasonal variation was observed in the sodium silicate dosage, which ranged from 9 to 11.0 mg/L as sodium silicate. The average dose of the data provided for sodium silicate was 11.4 mg/L as sodium silicate. Generally, the sodium silicate dose has been maintained around this average value, but it was noted that starting July 24, 2017, the sodium silicate dose was reportedly increased to 12-15 mg/L as sodium silicate. In comparison with the CTA, the average sodium silicate dose in 2014 was 8.3 mg/L as sodium silicate.

Figure 3-13 - Historic Pequannock WTP Chemical Dosages - Clarion, Lime, Sodium Silicate, PACI

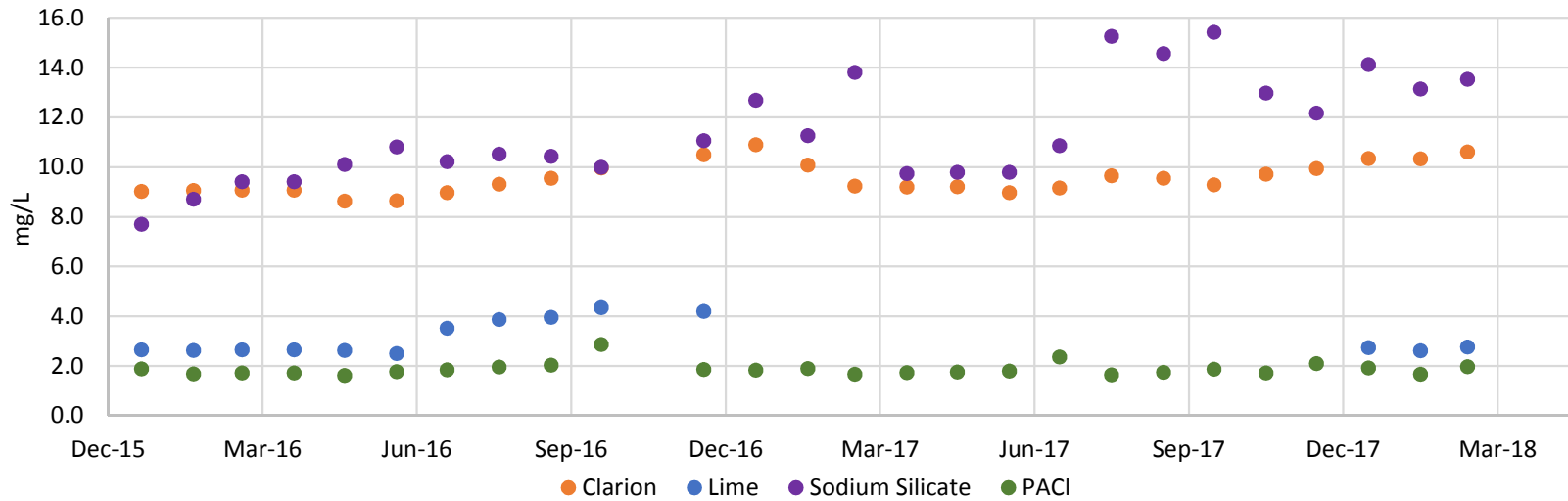
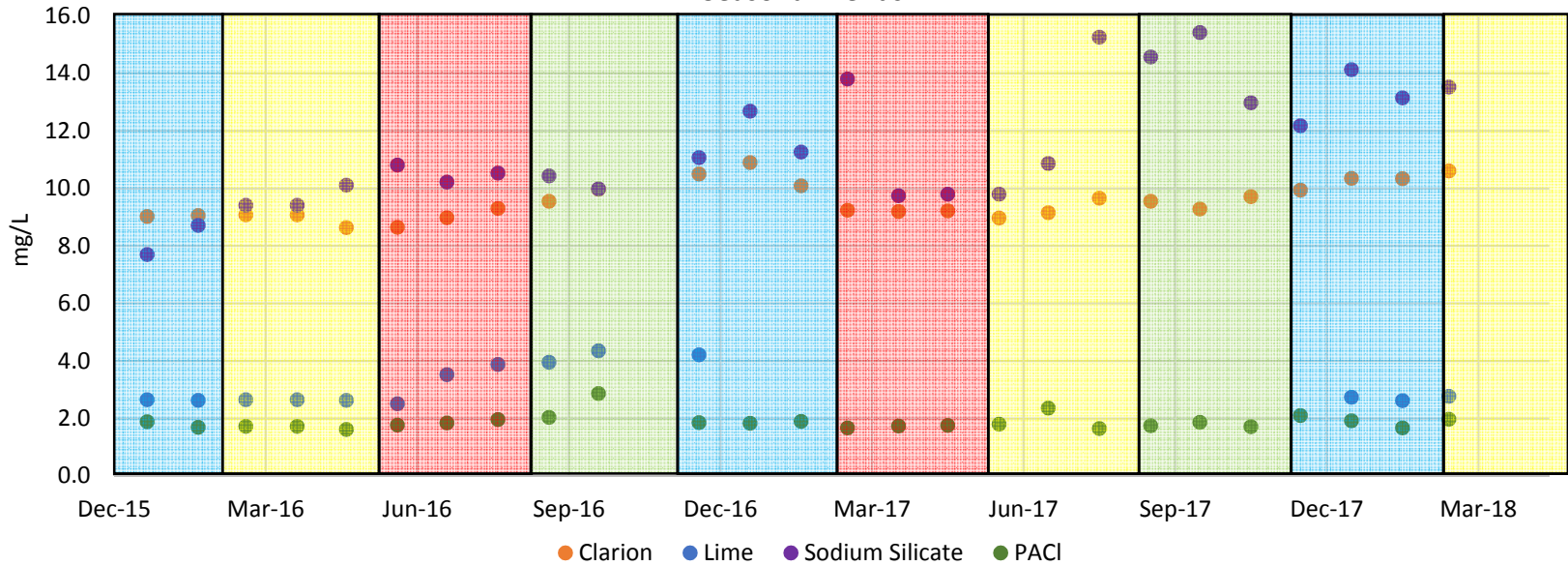


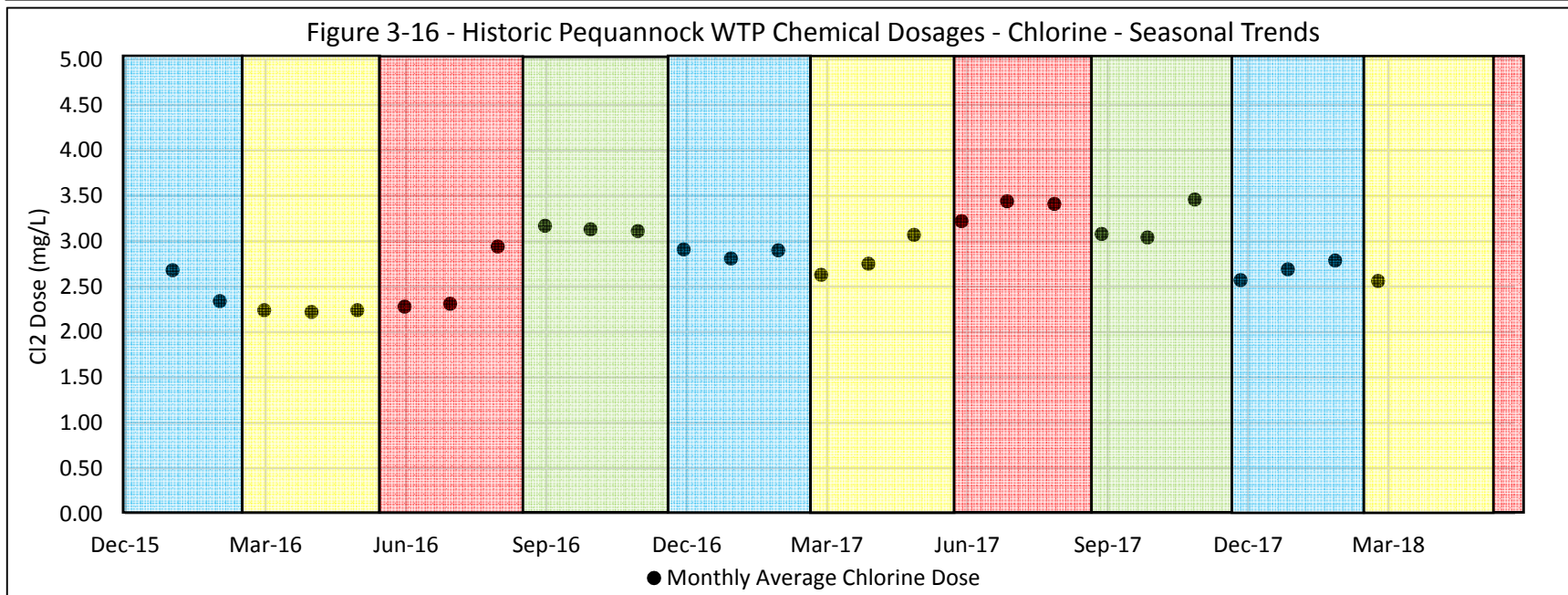
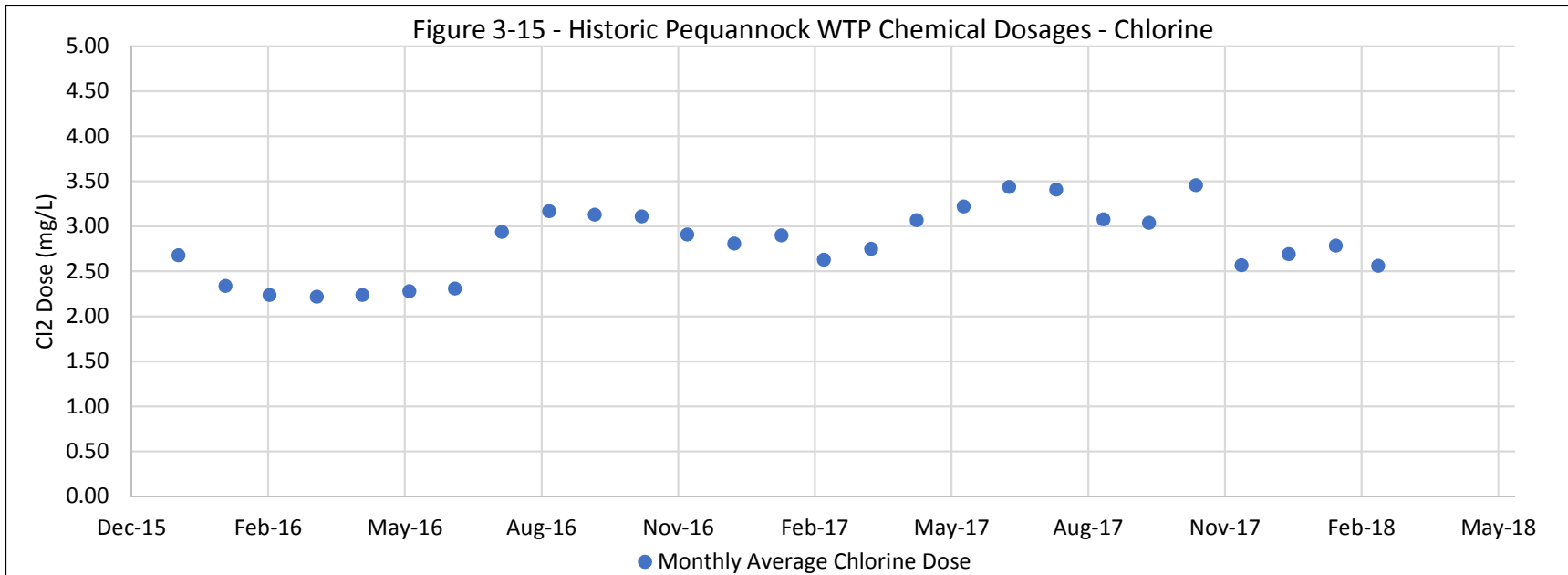
Figure 3-14 - Historic Pequannock WTP Chemical Dosages - Clarion, Lime, Sodium Silicate, PACI - Seasonal Trends



- No significant seasonal variation was observed in the PACl dosage, which ranged from 1.7 mg/L to 2.5 mg/L. The average dose of the data provided for PACl was 1.9 mg/L. Generally, the average PACl dose is consistent throughout the year and consistent with the average dose in 2014 which was 1.6 mg/L.

Figures 3-15 and 3-16 show the chemical dosage data and the seasonal trends for chlorine, from January 2016 – March 2018. January – March 2018 monthly dose averages were calculated from the use of chemical (lbs/month) and the 2017 daily flow to produce average seasonal data. The following remarks are noted from the data analysis for chlorine usage:

- The chlorine dosage ranges from 2.5 to 4.0 mg/L. The average dose of the data provided for chlorine is 3.0 mg/L (total of pre and post-chlorine addition). Generally, the chlorine dose has been maintained in this range. An increase in dosage in the summer months is observed, as expected due to warmer temperatures and chlorine's greater reactivity.
- The data does not include the sodium hypochlorite that is added at the Valley Road Rechlorination Station. The chlorine residual data from the addition of sodium hypochlorite at the Valley Road Rechlorination Station are included in Section 3.3.2.



3.3 Long-Term Water Quality Trends

This section reviews some of the longer-term trends of water quality parameters in Newark's system that have been variable over time and are known to have an impact on corrosion and corrosion control.

3.3.1 Historic pH – Pequannock WTP and Valley Road Rechlorination Station

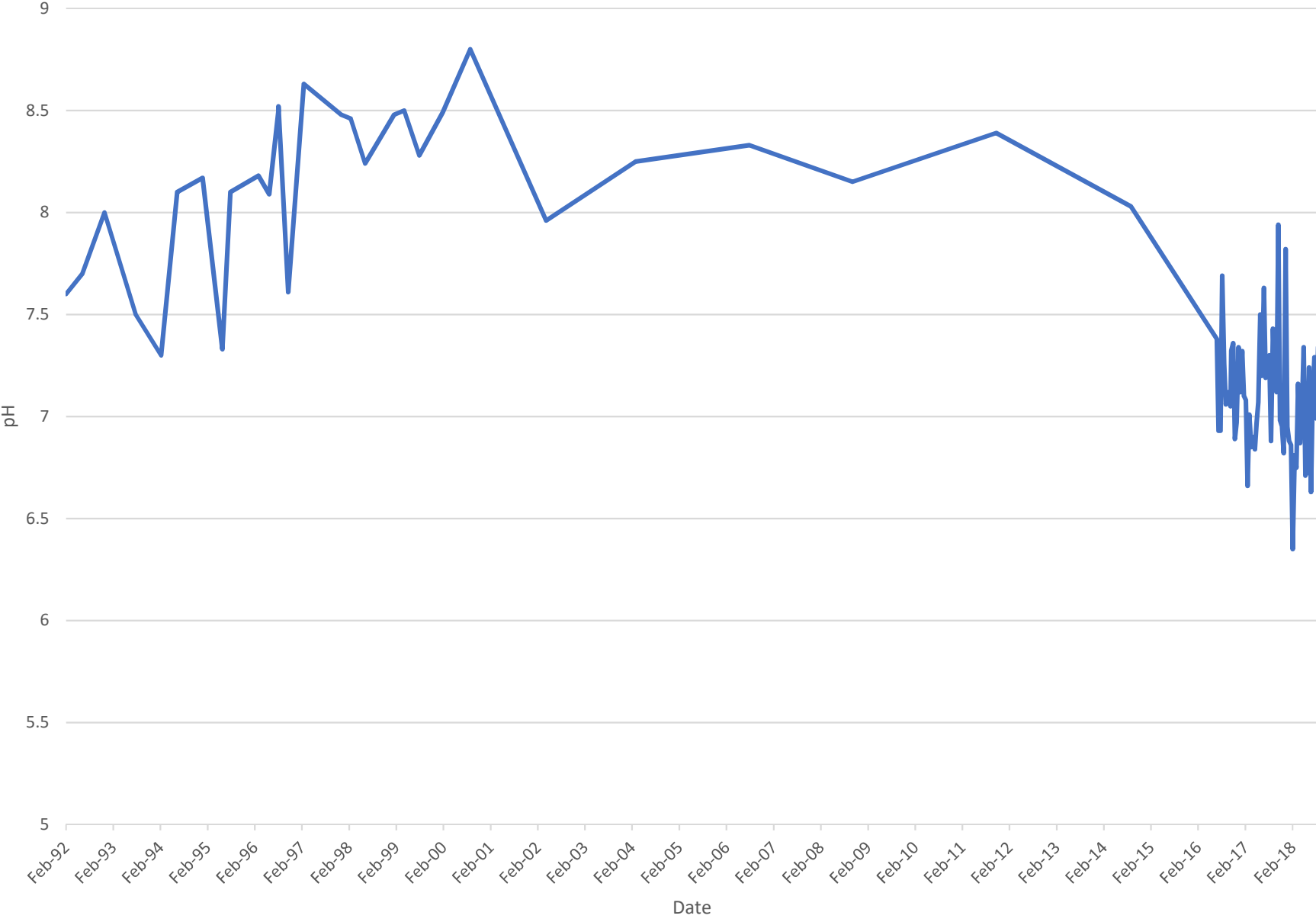
Historic pH data leaving the Pequannock WTP (at the "Test House") was available from February 1992 to September 2018 on Water Watch. **Figure 3-17** indicates that after the CCT study was performed in 1994 (See Section 2.1.1), Newark slowly raised its delivered water pH to around 8.5 from 1996 through 2002. In 2002, pH levels fell slightly to approximately 8.0 to 8.3. Although there are not many data points available, it appears that Newark generally maintained this level between 2002 and 2012. In 2013, pH levels fell to below 8.0 and have not been above 8.0 since. In the last 4 years, the average pH of the Pequannock WTP finished water was 7.1 based on data provided at the Test House. The averages over the last four recent years were as follows:

- 2015 – average pH of 7.26
- 2016 – average pH of 7.04
- 2017 – average pH of 7.00
- 2018 – average pH of 6.72 (January through August 2018)

The reduction in pH generally correlates to when monitoring for the Stage 2 Disinfectants and Disinfection Byproducts (DBPs) Rule commenced. Large systems were required to start monitoring and reporting DBPs using the Location Running Annual Average (LRAA) in 2012. It appears that Newark may have started decreasing pH around this time in an effort to meet the DBP regulatory requirements. Historic data was also available between 2005 and 2018 for the pH leaving the Valley Road Rechlorination Station before it enters the distribution system. **Figure 3-18** provides the pH data leaving the Rechlorination station during this period. The pH values at the Rechlorination Station tend to vary because of the low alkalinity (low buffer intensity), and are less than the pH of the Pequannock WTP finished water. Based on **Figure 3-18**, the average pH ranged from 7.6 to 8.0 from 2005 to 2012, with a few sustained periods above pH 8.0. After 2012, pH dropped to an average range of 7.5 to 7.7. pH increased to above 8.0 for a few months in 2015, and then decreased again in 2016, 2017 and 2018 to the current average around 7.0. A drop in pH starting in 2016 is apparent in both the Pequannock WTP delivered water (system POE) data as shown in **Figure 3-17** and the Valley Road Rechlorination Station data as shown in **Figure 3-18**.

Additional data points were provided for years prior to the silicate addition by Newark. In 1984, pH generally ranged between 7.8 and 8.0. In 1989-1990, pH ranged between 7.1 and 7.6.

Figure 3-17 – Historic Pequannock WTP Delivered Water pH



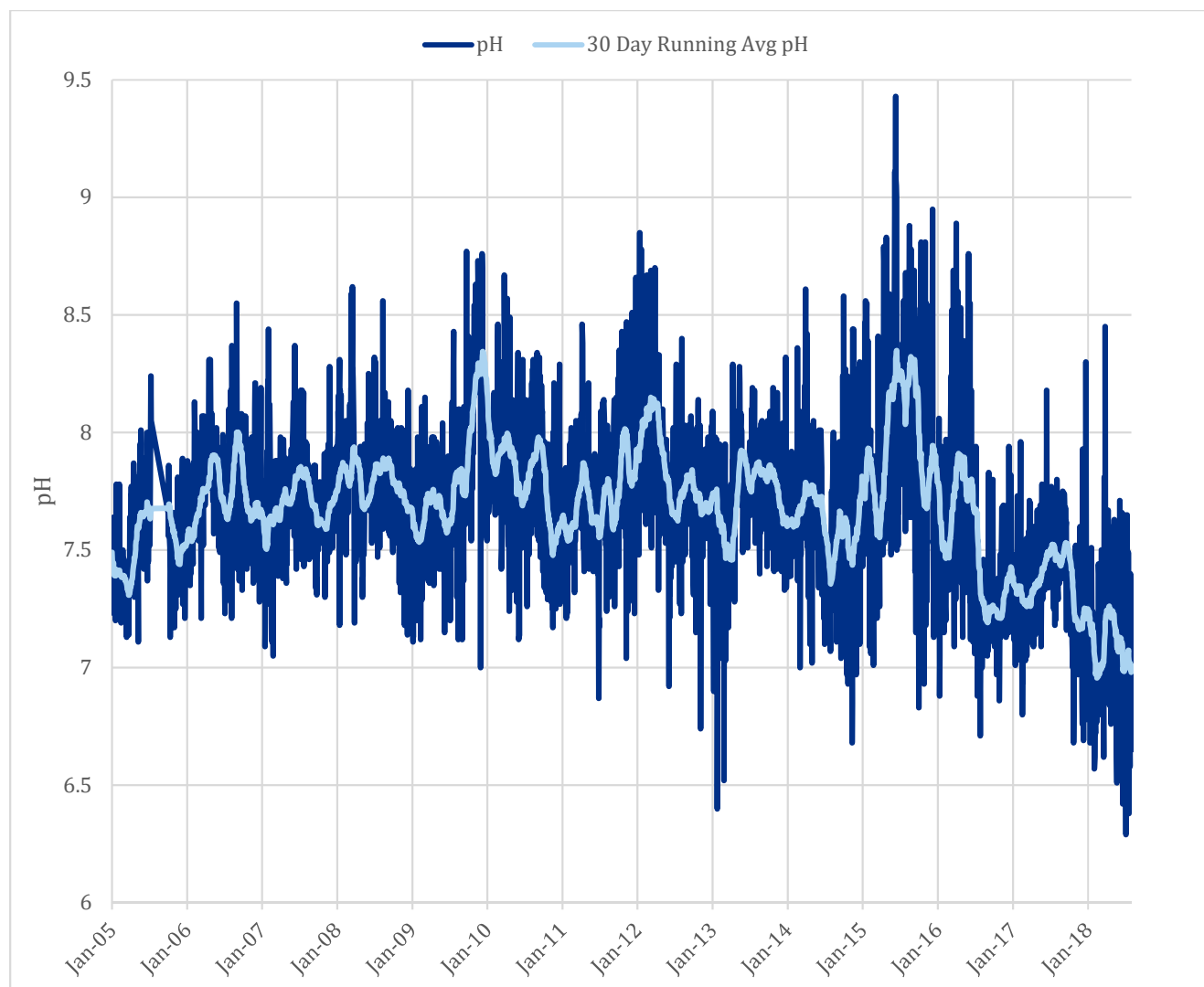


Figure 3-18 – Historic Valley Road Rechlorination Station pH (Distribution System POE) (2005 – 2018)

Regarding the daily fluctuations in pH experienced at the Pequannock WTP and the Valley Road Rechlorination Station, as shown in Figures 3-17 and 3-18, respectively, it is believed that the fluctuations are due primarily to the lime system operating challenges and not a result of buffering capacity. Newark has since made modifications to the system to increase the consistency of the lime dose at the Pequannock WTP. The alkalinity of the Pequannock water ranges between 10 and 35 mg/L as CaCO_3 with an average of approximately 22 mg/L as CaCO_3 and the DIC is approximately 8.5 mg/L as CaCO_3 . Based on water quality in other similar water systems, alkalinity and DIC levels in this range should be sufficient to maintain a consistent pH.

As mentioned, the fluctuations in pH experienced at the plant and across the system over the last few years are likely a result of operational challenges with the lime system at the Pequannock WTP, which have been recently addressed. This is evident from the historic daily fluctuations experienced in pH at the Pequannock WTP POE, while the pH across the distribution system on a given day is fairly consistent. This can be seen from comparing the pH values from the

Pequannock Gradient's WQPs on a given date. As shown in **Figure 3-19**, the pH range is fairly consistent across the large distribution system area.

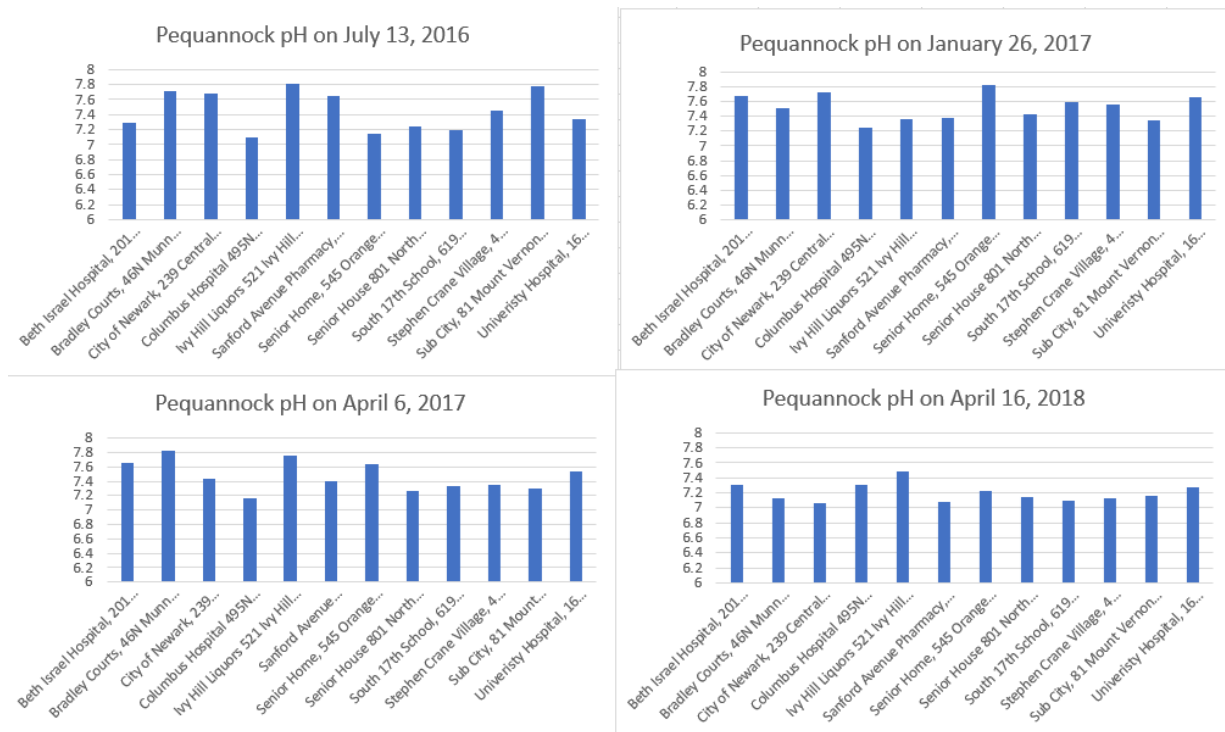


Figure 3-19 – Pequannock Gradient pH Values Across the Distribution System

3.3.2 Historic Chlorine Residual – Valley Road Rechlorination Station

Historic free chlorine residuals at the Valley Road Rechlorination Station, which is the point-of-entry into the distribution system for all but a small amount of water that is supplied upstream directly to the Township of Pequannock, were analyzed to determine changes over time. Daily “post-rechlorination” data were provided by Newark for the period between 2005 and 2018. The data, shown in **Figure 3-20**, indicate that chlorine residual leaving the rechlorination station generally ranged between 0.8 and 1.1 mg/L until about mid-2009, when chlorine residual trended steadily upwards to a range of 1.0 to 1.2 mg/L to mid-2015, and then continued to increase to a range of 1.1 to 1.3 mg/L until mid-2018. Current chlorine residual appears to be trending downward towards an average of 1.0 mg/L in the last few months. In general, the chlorine residuals have been held fairly constant on a 30-day running average over the dataset at the Valley Road Rechlorination Station, although there are some significant daily variations.

Additional chlorine residual data at the Valley Road Rechlorination Station was provided by Newark for years prior to the silicate addition. In 1984, chlorine residuals generally ranged between 1.0 and 1.2 mg/L. In 1989-1990, chlorine residual was reported to be consistently 1.0 mg/L.

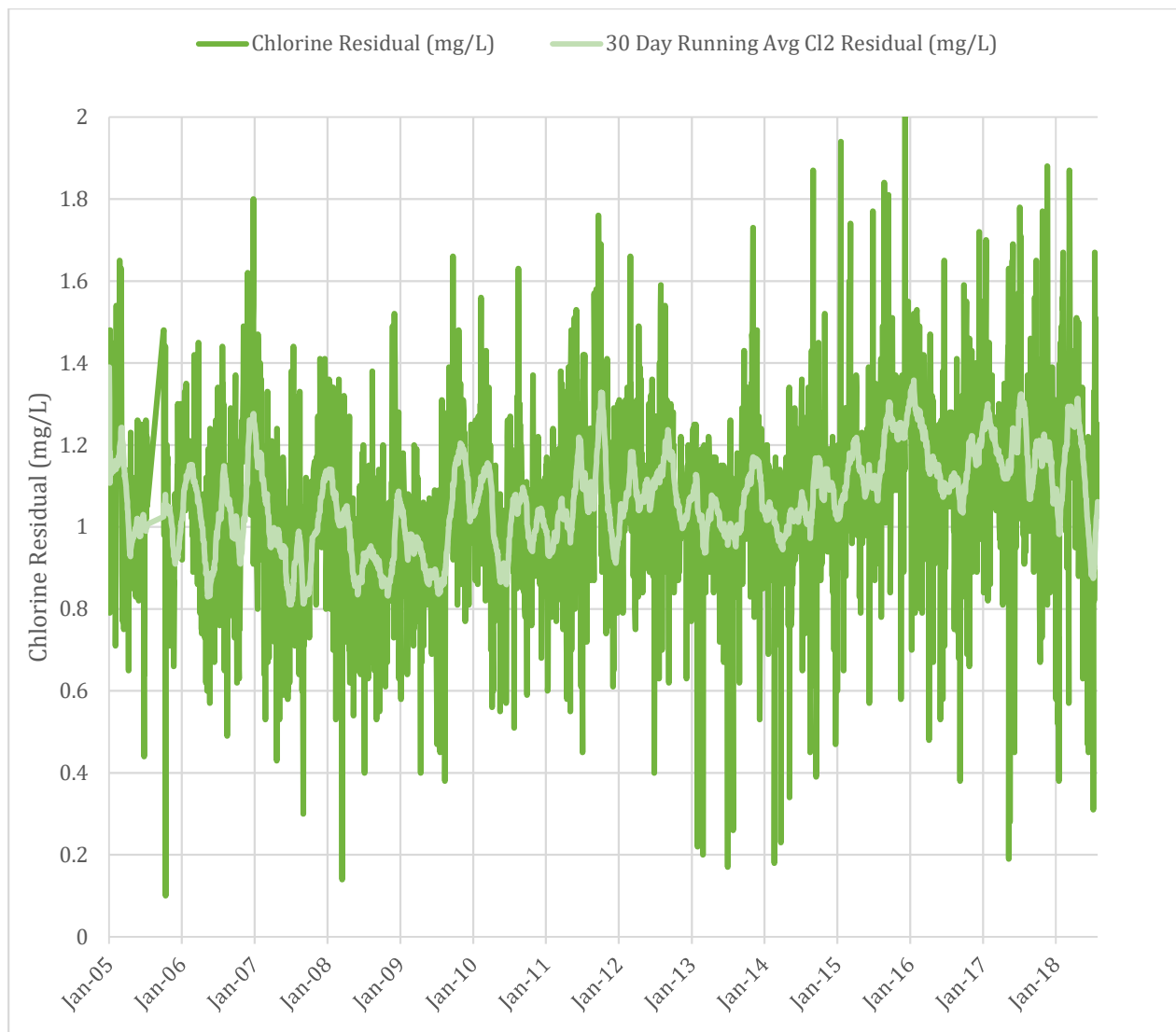


Figure 3-20 – Historic Valley Road Rechlorination Station Post Chlorine Residual (Distribution System POE) (2005 – 2018)

Section 4

Lead Sequential Sampling

The City of Newark conducted sequential sampling at two locations in September 2018. The purpose of this effort was to pinpoint potential sources of lead that exist within the service line and premise plumbing from the service connection in the street to the drinking water tap in the house. Sequential sampling is an additional tool to assist in developing an understanding of the system as part of the CCT optimization. The sources of lead at the tap measured in sequential samples include lead service lines, lead-based materials contained in the premise piping (e.g., leaded solder, brass/bronze fittings, galvanized piping), faucets, and water meters.

4.1 Sequential Sampling Program Protocol

The sequential sampling program consisted of collecting the full volume of water between the kitchen faucet and the water main in small increments allowing for the isolation of water from various plumbing components, such as, but not limited to, fixtures, valves, pipe materials and meters. A memorandum dated September 10, 2018 by CDM Smith titled “Sequential Sampling Program Protocol for Tracking Lead in Drinking Water” provided the protocol for performing the sequential sampling.

In general, the sequential sampling process consists of the following:

1. **Site Audit** - An initial visit to each home was conducted to document the cold-water piping, beginning at the faucet and traced back towards the water main in the street. This was used to calculate the volume in the water service line and determine the number and timing of samples needed for collection.
2. **Sample Collection and Analysis** - Sequential sampling is conducted after a stagnation period, between 6 to 12 hours, per the Lead and Copper Rule requirements. A 10-minute flush is conducted, without removing the aerators, prior to the stagnation period. Samples are taken at the kitchen sink in increments of 500 mL, or as determined by the site audit. A flushed sample is also taken at the end of the sequential program to test the water in the main. The aerator was not removed for the flushing or the sampling. Samples are analyzed for the following information:
 - *pH (first sample, a middle sample, and flushed final sample measured in the field)*
 - *Temperature (first sample, a middle sample, and flushed final sample measured in the field)*
 - *Free chlorine (first sample, a middle sample, and flushed final sample measured in the field)*
 - *Total Lead*
 - *Dissolved Lead*

- *Total Copper*
 - *Silica Residual (SiO₂) (first sample, a middle sample, and flushed final sample)*
 - *Alkalinity (first sample, a middle sample, and flushed final sample)*
 - *Conductivity (first sample, a middle sample, and flushed final sample)*
3. **Data Evaluation** – Once the samples are analyzed, the profile is plotted with cumulative volume on the X-axis and lead results on the Y-axis. Specific plumbing components are located along the service volume axis and the plumbing components most contributing to high lead values are noted.
 4. **Monitoring** – When the CCT is modified, the sequential sampling program is performed on a regular basis to ascertain the effectiveness of the new/modified CCT treatment.

4.2 Results of Newark's Initial Sequential Sampling

During the week of September 10, 2018, two residential locations were sampled for Newark's sequential sampling study as the initial baseline sampling, prior to any modifications to the CCT.

- Site A – South Ward
- Site B – North Ward

Each home has a lead service line and lead solder with copper indoor plumbing before the meter. Site A had cross-linked polyethylene (PEX) for the majority of their interior plumbing, with some sections of copper joined by lead solder. The locations of the sequential sampling sites are shown on **Figure 4-1**, including proximity to the harvested lead service lines that were sent to the EPA for pipe scale analysis discussed in Section 5.

Samples for total lead, dissolved lead and copper were taken every 500 mL as described in Section 4.1. It was estimated that Site A needed 15 samples and Site B needed 12 samples to encompass the entire interior plumbing and service line prior to reaching the main. After the final sample on the service line, the faucet was flushed for 10 minutes and another sample was taken at each house.

Background water quality collected at the time of the testing for each home is provided in **Table 4-1**. The background water quality was analyzed at the start of the testing (first draw sample), the middle of the testing (middle sample) and after a 10-minute flush (flushed sample). As can be seen in **Table 4-1**, the free chlorine residual is significantly less at Site A in South Ward than at Site B in the North Ward. This is to be expected as the North Ward is closer to the Valley Road Rechlorination Station and the South Ward is located at the other end of the distribution system.

Figure 4-1 – Map of Test Locations in Newark

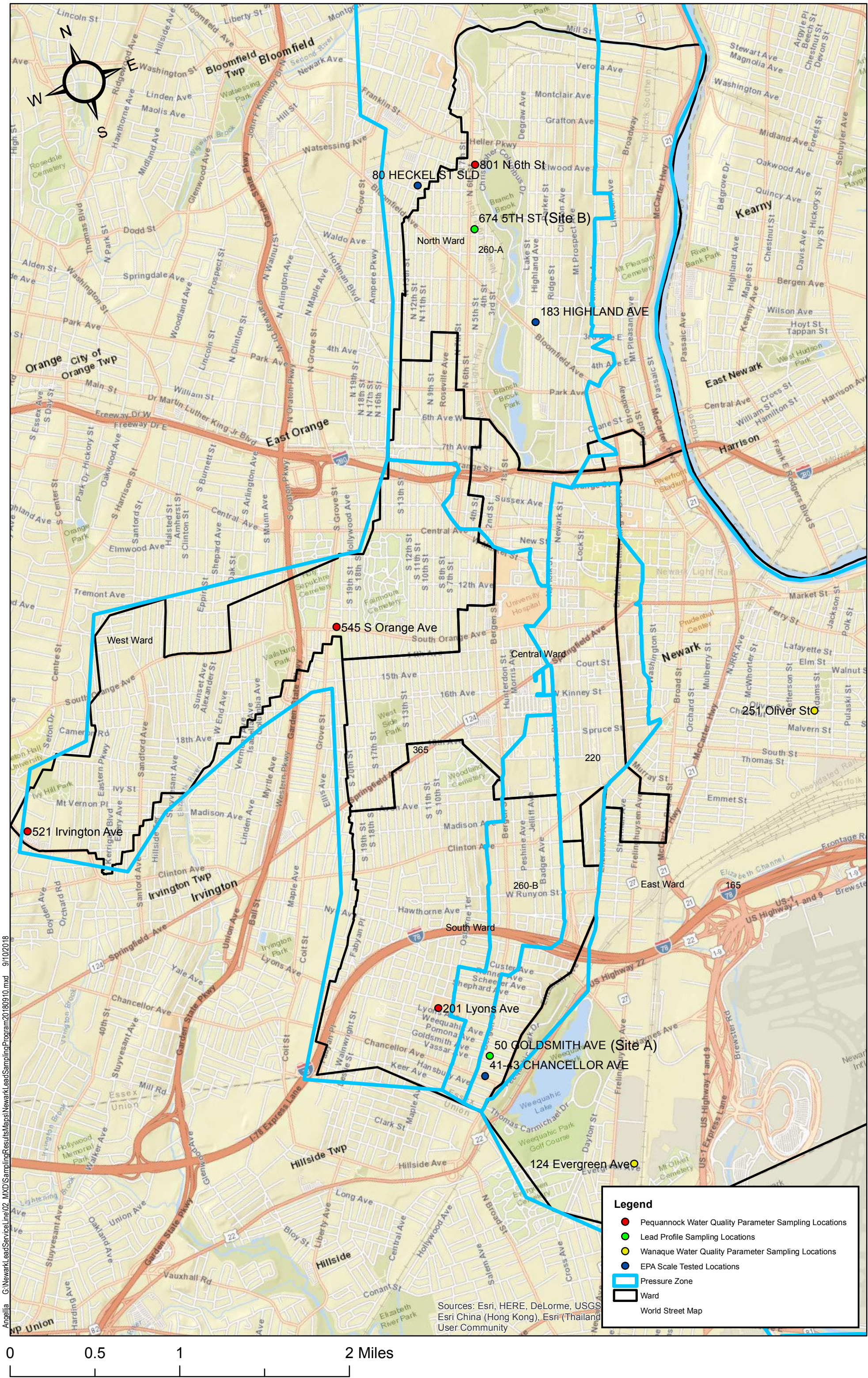


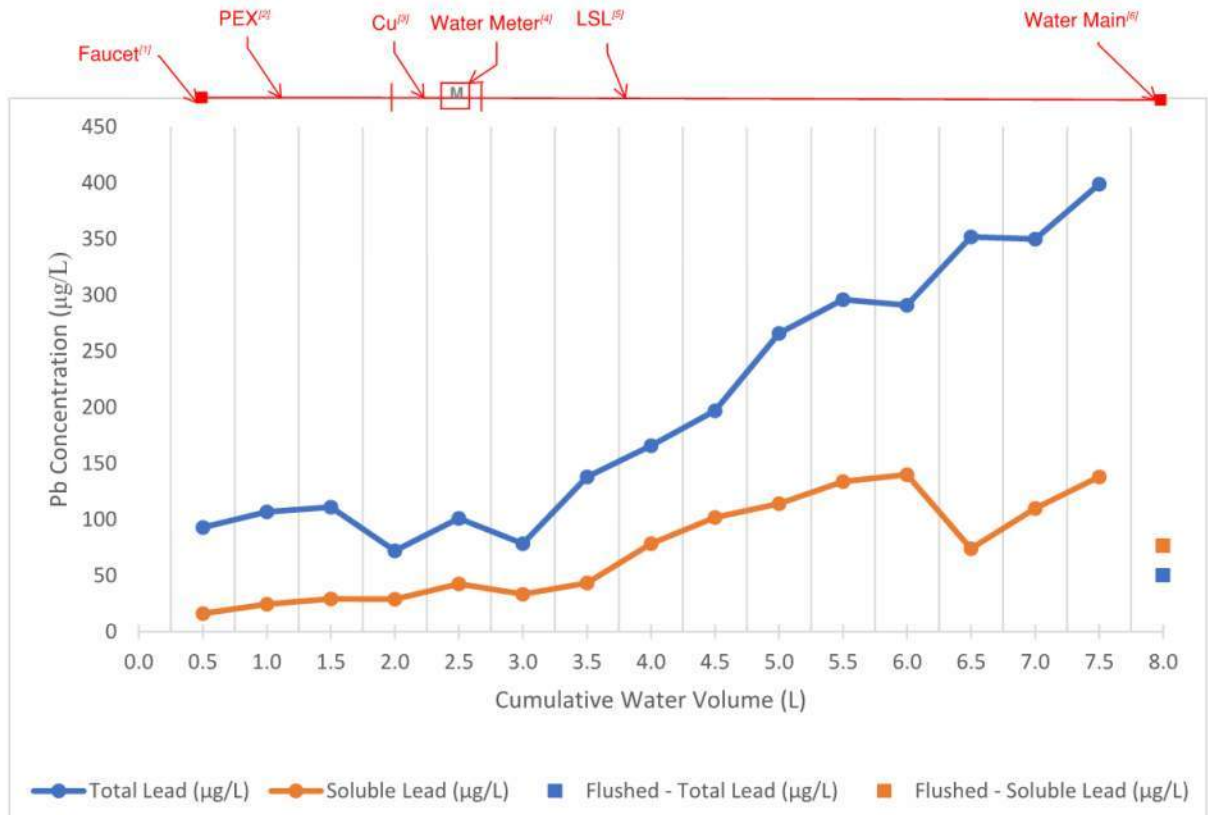
Table 4-1 – Water Quality Analysis at Sequential Sampling Sites

	Site A – South Ward			Site B – North Ward		
	First Draw Sample	Middle Sample	Flushed Sample	First Draw Sample	Middle Sample	Flushed Sample
pH	7.91	7.13	7.66	7.62	7.37	7.32
Temp (deg C)	20.9	20.7	21.6	21	22	22
Free Cl ₂ (mg/L)	0.02	0.04	0.21	0.22	1.21	1.04
Alkalinity (mg/L CaCO ₃)	34	34	36	34	35	33
Conductivity (uMhos/cm)	210	238	206	221	214	222
Silica (mg/L SiO ₂)	7.48	7.38	8.17	8.10	8.33	8.70

Total lead and soluble lead were plotted against the cumulative water volume in a profile to identify lead contributions from different plumbing materials. The difference between the total lead and soluble lead is insoluble or particulate lead. **Particulate lead is typically a result of scouring of deposits off the pipe wall or disturbing the scale layers that have formed over time, causing them to slough off the pipes. Soluble lead is dissolved lead that has leached from the piping into the water.** The profile for Site A is shown in **Figure 4-2** and the profile for Site B is shown in **Figure 4-3**. Plumbing fixtures and materials are shown above each profile for correlation of plumbing fixtures to the samples. The estimated total lead, soluble lead and particulate lead results in the samples at Site A and Site B corresponding with the figures are listed in **Table 4-2** and **Table 4-3**, respectively.

The following are the observations for the lead profile results for Site A – South Ward, as shown in **Figure 4-2** and listed in **Table 4-2**:

- The highest lead levels at this address were found in the lead service line (LSL) pipe section. Soluble lead peaked at 140 µg/L and total lead peaked at 399 µg/L.
- Significant particulate lead was found at this address. The particulate lead may be a sign of the breakdown of a protective scale on the LSL which is further discussed in Section 5. It may also indicate that some particulate lead collected on the aerator after the flushing (or prior to that) and was present throughout the sampling.
- **Both soluble and insoluble lead levels are high, indicating the current CCT is not optimized.**
- Silica concentrations were an average of 7.68 mg/L as SiO₂, which generally coincides with the Pequannock WTP delivered water concentrations measured at the Test House.



[1] Kitchen Faucet Location, [2] Cross-Linked Polyethylene Pipe Segment, [3] Copper Pipe Segment, [4] Water Meter Location, [5] Lead Service Line Pipe Segment, [6] Water Main Location

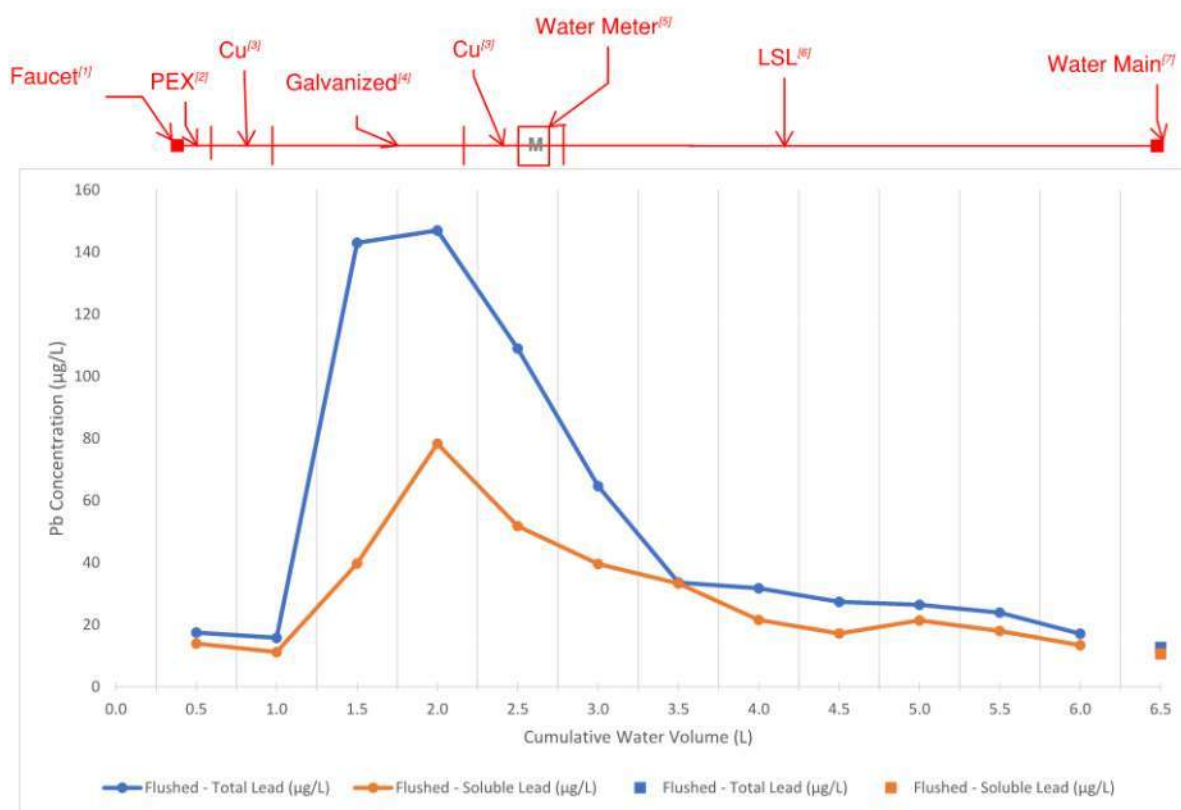
Figure 4-2 – Site A – South Ward Lead Profile – September 10, 2018

Table 4-2 – Site A – South Ward Lead Results

Sample ID	Total Lead (µg/L)	Soluble Lead (µg/L)	Particulate Lead (µg/L)
A1	93.1	16.2	76.9
A2	107	24.6	82.4
A3	111	29.4	81.6
A4	72.2	29.1	43.1
A5	101	42.5	58.5
A6	78.6	33.4	45.2
A7	138	43.4	94.6
A8	166	78.4	87.6
A9	197	102	95
A10	266	114	152
A11	296	134	162
A12	291	140	151
A13	352	74	278
A14	350	110	240
A15	399	138	261
Flushed	50.5	76.6	0

The following are the observations for the lead profile results for Site B – North Ward, as shown in **Figure 4-3** and listed in **Table 4-3**:

- The highest lead levels at this address were found in the galvanized steel pipe section that is likely lead-lined, and the copper pipe section with lead-soldered joints. Soluble lead peaked at 78.3 µg/L and total lead peaked at 147 µg/L.
- Particulate lead was evident in the pipeline for 3 samples – liters 2.0, 2.5 and 3.0. The high particulate lead levels may be a sign of breakdown of a protective scale, which is further discussed in Section 5.
- Both soluble and insoluble lead levels are high, indicating the current CCT is not optimized.
- Silica concentrations were an average of 8.38 mg/L as SiO₂, which generally coincides with the Pequannock WTP delivered water concentrations measured at the Test House. The silica concentrations found in the North Ward were slightly greater than the concentrations found in the South Ward site (Site A).



[1] Kitchen Faucet Location, [2] Cross-Linked Polyethylene Pipe Segment, [3] Copper Pipe Segment, [4] Galvanized Steel Pipe Segment
 [5] Water Meter Location, [6] Lead Service Line Pipe Segment, [7] Water Main Location

Figure 4-3 – Site B – North Ward Lead Profile – September 11, 2018

Table 4-3 – Site B – North Ward Lead Results

Sample ID	Total Lead (µg/L)	Soluble Lead (µg/L)	Particulate Lead (µg/L)
B1	17.5	13.9	3.6
B2	15.8	11.2	4.6
B3	143	39.7	103.3
B4	147	78.3	68.7
B5	109	51.8	57.2
B6	64.6	39.6	25
B7	33.6	33.3	0.3
B8	31.7	21.5	10.2
B9	27.4	17.2	10.2
B10	26.4	21.4	5
B11	23.9	18	5.9
B12	17.1	13.4	3.7
Flushed	12.8	10.5	2.3

4.3 Discussion

The sequential sampling performed at the two locations on opposite ends of Newark's distribution system indicates that the current CCT is not effective at controlling soluble lead release into Newark's drinking water. Despite dissolved silica concentrations of approximately 8 mg/L as SiO₂ and the existence of a silica crust on the pipe walls (see EPA scale analysis in Section 5), the soluble lead concentration is still well above the EPA's LCR Action Level for lead. In addition, if a passivating scale (a protective layer on the pipe wall formed through chemical reactions between the water and carrier pipe) was intact and functioning as a lead-containing mineral scale to limit lead solubility, the lead levels would be expected to be much lower (Boyd, et al., 2008) than what was found. This indicates that the scales on the pipes in these two homes are not functioning as protective corrosion control scales and may be breaking down under the current water quality conditions. Regarding particulate lead, both homes had appreciable particulate lead in their tap water at the time the sequential sampling was conducted. This could be a result of lead-containing sediment in the service line, particulates that collected in the aerator, active breakdown of lead mineral scales on the pipe walls, or most likely a combination of these factors. After the sampling was conducted, it was reported that the home in the South Ward (Site A) has performed some recent plumbing improvements by replacing sections of copper and galvanized pipe with new copper and new PEX plumbing. Both homeowners were contacted to take precautions against lead contamination and Newark replaced their lead service lines with copper lines.

Lead sequential sampling is a useful tool to isolate the source of lead in tap water in a given home, to evaluate the magnitude of the current lead exposure to the public, and to evaluate differences in lead levels that may exist throughout the distribution system. It is recommended that additional sequential sampling be performed in homes in other Wards in Newark's distribution system. It is also recommended that Site A be re-tested after cleaning out the aerator and flushing

without the aerator to see if the high particulate lead results were due to a build-up of particulate lead behind the aerator.

In addition to evaluating the current level of lead in the Newark system, lead sequential sampling can be used as a tool to monitor the effectiveness of CCT implementation. It is recommended that a few homes be sampled monthly during any modifications to the system's CCT until lead levels stabilize.

Section 5

Pipe Scale Analysis

In February and March 2018, Newark sent three lead service pipes from the City's distribution system to the EPA Advanced Materials and Solids Analysis Research Core in Cincinnati, OH for characterization of the solid phases on the pipe walls. The pipes came from the following addresses:

- 43 Chancellor Avenue (South Ward)
- 80 Heckel Street (North Ward)
- 183 Highland Avenue (North Ward)

In October 2018, Newark sent the lead service pipes from the locations where sequential sampling was conducted in September 2018, to the EPA Advanced Materials and Solids Analysis Research Core in Cincinnati, OH for analyzing. The pipes came from the following locations, see Section 4 for reference:

- Site A – 50 Goldsmith Avenue (South Ward)
- Site B – 674 N 5th Street (North Ward)

The locations listed above are shown on the map in **Figure 4-1**. This section presents the results of the analyses that EPA performed on the pipe scales.

Analysis of scales from pipes that reflect actual distribution system conditions provides a direct indication of the effectiveness of a current treatment process to control lead release. Knowledge of the characteristics and behavior of the lead solids that have been formed on the pipe walls can be integrated with water quality and operational information to understand mechanisms of corrosion inhibition, speciation of metals, and predictions of lead mobility/stability, and can assist in implementation of corrective treatment changes. Knowing how a contaminant is chemically associated in distribution system scale materials can help with estimating the probability of unintended adverse consequences of treatment or water quality changes.

5.1 EPA Scale Analysis Testing and Results

The EPA conducted the following tests on the three lead pipes:

- X-ray diffraction (XRD) analysis – identifies crystalline mineral compounds
- Scanning electron microscopy (SEM)/Energy dispersive spectroscopy (EDS) elemental mapping – identifies general areas where different elements exist within the scale

The testing evaluated the scales in different layers on the pipe walls, which can indicate the history of water chemistry impacts over time. The technique involves separating each solid phase

layer for analysis, from the outermost layer (the layer in direct contact with the flowing water) to the innermost layer (the layer directly against the lead pipe wall).

The EPA results for 43 Chancellor Avenue, 80 Heckel Street and 183 Highland Avenue were provided on September 21, 2018. The EPA results for 50 Goldsmith Avenue and 674 5th Street were provided on December 14, 2018. **Figures 5-1 through 5-5** show images of the pipe scales in cross section for the each of the five sites. The entire EPA report is included as **Appendix A**. A summary of the compounds found at each location from the outermost layer in contact with the flowing water (L1) to the innermost layer adjacent to the pipe wall (highest “L”) is provided in **Table 5-1**. The “+” indicates the relative presence of a compound in the scale analyzed.



Figure 5-1 – Lead Scale Images for Pipe Extracted from 43 Chancellor Avenue



Figure 5-2 – Lead Scale Images for Pipe Extracted from 80 Heckel Street



Cross section from 183 Highland Ave.

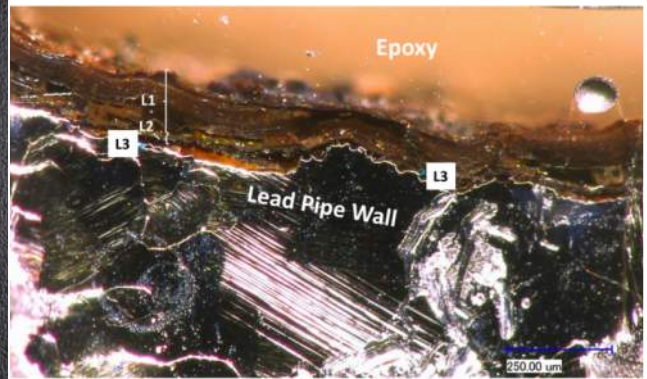


Figure 5-3 – Lead Scale Images for Pipe Extracted from 183 Highland Avenue



Cross section from Site A.

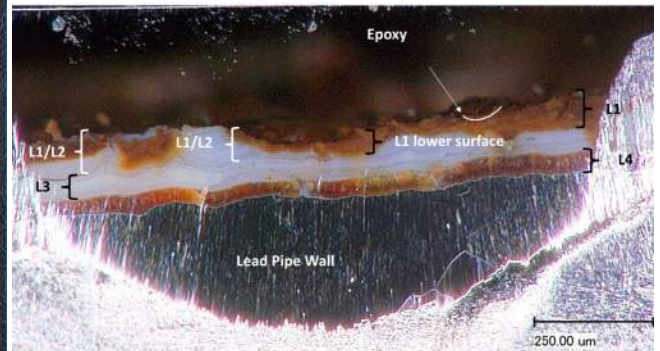


Figure 5-4 – Lead Scale Images for Pipe Extracted from 50 Goldsmith Avenue



Cross section from Site B.

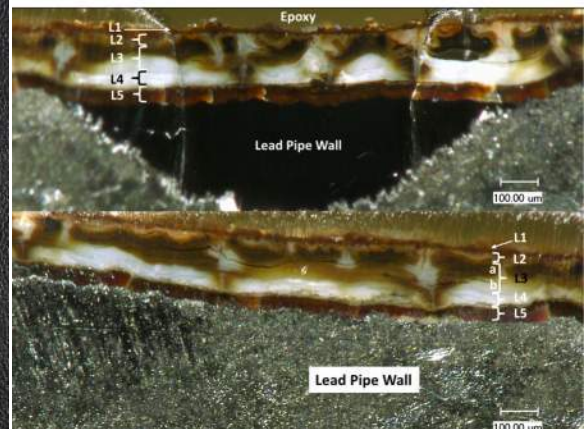
Figure 5-5 – Lead Scale Images for Pipe Extracted from 674 5th Street

Table 5-1 – General Characterization of Solid Phases in Pipe Deposits

Location	Layer	Hydrocerussite $Pb_3(CO_3)_2(OH)_2$	Cerussite $Pb(CO_3)$	Plattnerite PbO_2	Litharge PbO	Massicot PbO	Scrutinyite PbO_2
43 Chancellor Avenue (South Ward)	L1	++	+++	+	none	none	none
	L2	+++	++	+	none	none	none
	L3	+++	++	++	none	none	none
	L4	+++	+	++	+	none	none
	L5	++	+	none	+++	+	none
80 Heckel Street (North Ward)	L1	+++	+	+++	none	none	+
	L2	++	+	+++	none	none	+
	L3	++	none	+	+++	none	+
183 Highland Avenue (North Ward)	L1	+	none	+++	none	+	none
	L2	+++	none	+++	none	+	none
	L3	+	none	+	+++	+	none
50 Goldsmith (South Ward)	L1	+++	+	+	none	none	none
	L1/L2	+++	+	++	none	none	none
	L3	+++	+	+	none	none	none
	L4	++	+++	none	+++	none	none
674 5th Street (North Ward)	L1	+++	++	+++	none	none	none
	L2	+++	++	+++	none	none	none
	L3	+++	+	+++	none	none	none
	L4	+++	+	++	none	none	none
	L5	No Data	No Data	No Data	+++ ^[1]	No Data	No Data

Note: +++ = predominant, ++ = moderate, and + = trace/minor

^[1] L5 was not sampled due to breaking and was noted to most likely be Litharge (PbO) based on color and texture

The scales found on the outermost layers were primarily hydrocerussite, along with cerussite and plattnerite. Hydrocerussite and cerussite are divalent Pb(II) compounds that are carbonate-based scales. In carbonate-based scales, the hydroxide (OH^-), carbonate (CO_3^{2-}), or bicarbonate (HCO_3^-) ions complex with the metal (i.e., lead) to form insoluble metal/hydroxide/carbonate compounds on the pipe walls. These different lead minerals have varying degrees of solubility. Cerussite is the most stable Pb(II) phase at pH 8–8.5. Cerussite is more soluble than hydrocerussite, which is the most stable Pb(II) phase at higher pH (≥ 9.0). It is unusual to find hydrocerussite as the dominant mineral phase at Newark's current operating range around pH 7.4.

Plattnerite (PbO_2) is a tetravalent Pb(IV) compound that is formed over time in waters with high redox potential (ORP). It is reported in the literature that a high ORP can be achieved with free chlorine at levels typically over 1.5 mg/L, and that the rate of formation of PbO_2 appears to increase with increasing pH (Boyd, et al., 2008). Pb(IV) has been observed in systems with free chlorine residuals less than 1.5 mg/L, including Newark. ORP data is not available from within the Newark distribution system so correlations with chlorine residual are not possible. Under these

conditions, PbO_2 typically dominates or coexists with Pb(II) mineral forms including hydrocerussite and cerussite. Plattnerite is less soluble than hydrocerussite and cerussite, making plattnerite more effective at achieving low lead levels when the proper (high ORP) water chemistry is maintained.

The pipe scales did not contain evidence of any crystalline Si-Pb compounds, indicating that silicate complexation with lead is not taking place to control soluble lead levels. However, a silica crust (SiO_2) was found on all pipes. The silica crust was found to be relatively porous and therefore not acting as an effective barrier against the outward flux of lead released from the pipe as the passivating lead layers (mainly plattnerite and hydrocerussite) were found behind the silica crust.

5.2 EPA Elemental Analysis Testing and Results

An elemental analysis was also performed via X-ray fluorescence (XRF) on the same five lead services lines discussed in **Section 5.1**. The XRF technology is able to assess the inorganic elemental composition of solid layers on the lead service lines through the solids extraction process. The EPA XRF results (Appendix A), provide the concentration of inorganic elements, expressed as micrograms per gram of solid (parts per million) or weight percent (AWWA, 2017).

It should be noted that at the time the results were provided by the EPA, the XRF was not calibrated for carbon; should carbon concentrations have been added, the accuracy of the Pb results would improve. However, the results are considered of sufficient accuracy to provide meaningful information.

To put the results below into context, the percentage (by weight) of lead (Pb) in the predominant scale complexes found on the pipes is 77.5% Pb in cerussite ($\text{Pb(CO}_3\text{)}$), 80.1% Pb in hydrocerussite ($\text{Pb}_3(\text{CO}_3)_2(\text{OH}_2)$), 86.6% Pb in Plattnerite (PbO_2), and 92.8% Pb in Litharge (PbO).

Table 5-2 provides a summary of the elemental data for the most common components found in each layer for the five locations. The sites are discussed individually below. The terminology “inner” refers to the scale layer directly against the lead pipe wall whereas “outer” refers to the scale layer in direct contact with the flowing water. The outermost layer is labeled as L1 and increases numerically, until reaching the innermost layer.

Table 5-2 – Summary of Scale Composition Elemental Analysis Results

Location	Layer	Elemental* % by Weight						
		Pb	Si	Fe	Al	Mn	Na	K
43 Chancellor Avenue (South Ward)	L1	69.44	2.90	4.77	1.49	< 0.5	No data	No data
	L2	92.14	< 0.50	< 0.50	< 0.50	< 0.50		
	L3	No data						
	L4	95.1	< 0.50	< 0.50	< 0.50	No data		
	L5	99.33	< 0.50	< 0.50	< 0.50			
80 Heckel Street (North Ward)	L1	75.37	2.63	1.23	1.61	1.8	No data	No data
	L2	96.39	0.61	< 0.50	< 0.50	< 0.50		
	L3	98.23	< 0.50	< 0.50	< 0.50	No data		

Location	Layer	Elemental* % by Weight						
		Pb	Si	Fe	Al	Mn	Na	K
183 Highland Avenue (North Ward)	L1	93.16	2.52	< 0.50	0.63	< 0.50	< 0.50	No data
	L2	40.57	30.15	0.94	2.42	< 0.50	0.91	0.72
	L3	97.74	1.42	< 0.50	< 0.50	No data	No data	No data
50 Goldsmith Ave (South Ward)	L1/L2	89.15	1.15	1.02	< 0.50	< 0.50	No data	No data
	L3	89.01	< 0.50	< 0.50	< 0.50	No data		
	L4	86.68	< 0.50	< 0.50	No data	No data		
674 5 th Street (North Ward)	L1	82.23	2.60	3.51	1.97	1.00	No data	No data
	L2	89.12	0.89	1.07	0.65	< 0.50		
	L3	91.08	< 0.50	0.54	< 0.50	< 0.50		
	L4	90.55	< 0.50	< 0.50	< 0.50	No data		
	L5	No data						

*Pb = lead; Si = silica; Fe = iron; Al = aluminum; Mn = manganese; Na = sodium; K = potassium

43 Chancellor Avenue

The outermost layer had the most amount of silica (Si), iron (Fe) and aluminum (Al) which substantially decreased in the subsequent layers. The outermost layer had the lowest amount of lead and lead increased significantly in the innermost layer. The general trend of increasing Pb from the outer to inner layers corresponds to the scale composition consisting of lead carbonates to a mix of lead carbonate with PbO₂, then to PbO-dominated in L5, as presented in **Table 5-1**. The increase in Pb in the layers moving from outer to inner is expected as the inner layers are closer to the source of lead (the pipe). Other elements were traced in the lead layers, but were less than 0.5% by weight, such as calcium (Ca), copper (Cu), nickel (Ni), phosphorous (P), sulfur (S), antimony (Sb), and zinc (Zn).

80 Heckel Street

The results are similar to those at 43 Chancellor Avenue, where the outermost layer had the greatest amount of Si, Fe Al and Mn, which substantially decreased in the inner layers (L1 to L3); however, the outermost layer had a higher percentage of Pb than 43 Chancellor, which also significantly increased in L3. The general trend of increasing Pb from the outer to inner layers corresponds to the scale composition consisting of a mix of lead carbonate and PbO₂ in L1, to less lead carbonate in L2, and then PbO-dominated in L3. Other elements were traced in the lead layers, but were less than 0.5% by weight, such as bismuth (Bi), Ca, Cu, Ni, P, S, and Zn.

183 Highland Avenue

The results at this location were different than the other two lead service line locations. The percentage of Pb was high in L1, dropped quite sharply in L2, and increased again in L3. This same pattern is demonstrated for Si, and to a lesser extent for Fe and Al. Traces of sodium (Na) increased in L2 and traces of potassium (K) were only found in L2. It cannot be determined how much of the Si in L2 originated from the quartz grains (trench sediment contamination) on the surface of the scale as opposed to being a result of CCT. However, it is speculated that the high percentage of Si and low percentage of Pb in L2 was noted to be likely due to the large amount of quartz sediment incorporated into the sample that was sent for analysis. Other elements were

traced in the lead layers, but were less than 0.5% by weight, such as Bi, Ca, Cu, Mg, Ni, P, S, titanium (Ti) and Zn.

50 Goldsmith Avenue

The scale analysis results for 50 Goldsmith Avenue were different from 43 Chancellor Avenue, which is also located in the South Ward and nearby. This is due to having layers of scale (L1-L4) already sloughed off in multiple areas while the lead service line was in service, as seen in **Figure 5-4**. However, both south ward locations had a predominant amount of litharge (PbO) in the innermost layer. The scale analysis and conditioning of the lead pipe agree with the sequential sampling results. As demonstrated in **Figure 4-2**, the lead continuously increased and lowered after flushing for 10 minutes. There are sections where the lead pipe would have been in direct contact with the water, due to segments of layered scaling sloughing off.

The percentage of Pb remained high across all layers, with a very slight decrease from the outer to the innermost layers. It was noted that there was insufficient sample for analysis of L1 by itself and L1/L2 were combined for analysis. The elements Si and Fe had percent by weight values of 1.15 and 1.02, respectfully, in L1/L2 that decreased to trace amounts reaching the innermost layer of the pipe. It was noted that some portion of the Si concentration observed in L1/L2 was contributed by sand (quartz) grains that contaminated the scale and originated from the trench sediment. Other elements were traced in the lead layers, but were less than 0.5% by weight, such as Al, Ca, Cr, Cu, Mn, Ni, P, and S. Although present in low amounts (less than 0.5% by weight), P concentrations observed at 50 Goldsmith Avenue were similar to concentrations observed at 43 Chancellor, which is located just a few streets away.

674 5th Street

The scale analysis results at this location are different than the other two North Ward service line locations. The outermost layer was predominantly hydrocerussite and plattnerite with a moderate amount of cerussite. L2 and L3 remain the same as L1, with regards to the lead compound. L3 also consisted of a complex laterally-heterogeneous mix of plattnerite and (hydroxy)carbonates (i.e., cerussite and hydrocerussite). Even though the innermost layer L5 was not tested sample due to it breaking into fragments, it was noted that it was composed mainly of litharge (PbO), based on color and texture, which is similar to both the other north ward scale analysis results.

The scale composition elemental analysis for 674 5th Street followed similar patterns to 80 Heckel St, which is also located in the North Ward. The percentage of Pb by weight followed an increase from the outermost to innermost layer. The outermost layer also had the highest amount of Si, Fe, Al and Mn, which decreased from the outer to inner layers. 674 5th Street had a higher elemental percentage by weight for Pb and Fe than 80 Heckel), but the Si and Al were within a 0.5% range. Additionally, 80 Heckel Street had a slightly higher elemental percentage by weight of Mn than 674 5th Street in the outermost layer. Other elements were traced in the lead layers, but were less than 0.5% by weight, such as Ca, chlorine (Cl), Cu, neodymium (Nd), Ni, P, S, Zn. Although very low, the P at 674 5th Street was similar to that at 43 Chancellor. The 5th street pipe is located in the North Ward with 80 Heckel and 183 Highland as its nearest neighbors, both of which have maximum XRF results for P as 0.03 % by weight.

5.3 Analysis of Results

5.3.1 Comparison of Sequential Sampling Results and Scale Analysis

More dominant plattnerite scales were found on the pipes harvested in the North Ward at 80 Heckel Street, 183 Highland Street and 674 5th Street where the chlorine residuals have likely always been the highest in the system because they are closest to the Rechlorination Station. This was confirmed by the lead sequential sampling results presented in Section 4. The North Ward address (674 5th Street) had a chlorine residual over 1.0 mg/L while the South Ward site (50 Goldsmith Avenue) had a chlorine residual of 0.21 mg/L in the water main and 0.04 mg/L in the service line. **Table 5-3** correlates the information from the EPA pipe scale analysis with the lead sequential sampling study based on proximity to each other. The test locations relative to each other geographically are provided in **Figure 4-1**. The solid phase (scale) minerals in the last column of **Table 5-3** are listed from most prominent to least prominent.

Table 5-3 – Comparison of Lead Sequential Sampling Data and EPA Scale Analysis Results

General Location	Chlorine Residual (mg/L)		pH		Most Prominent Scale Compounds Found
	First Draw	Flushed Sample	First Draw	Flushed Sample	
North Ward	0.22	1.04	7.62	7.32	Plattnerite > hydrocerussite > litharge
South Ward	0.02	0.21	7.91	7.66	Hydrocerussite > cerussite > plattnerite

As shown in **Tables 5-1** and **5-3**, the pipes from the South Ward (43 Chancellor Avenue and 50 Goldsmith Avenue) tested by EPA showed predominantly hydrocerussite, and cerussite scales, which are more soluble than plattnerite scales. This was also evident in the lead sequential sampling results presented in Section 4 where the soluble lead levels were higher at the South Ward profile (50 Goldsmith Avenue) than the North Ward profile (674 5th Street). This indicates that the current pipe scale in the South Ward is less effective at controlling soluble lead than the North Ward scale. The high particulate lead content also indicated that the scale could be sloughing off due to its porosity and physical instability. This was confirmed with the scale analysis results.

5.3.2 Formation of Tetravalent Lead (Pb(IV)) Scales

As noted above, free chlorine residual is an indicator of the ORP of the water. In highly oxidizing waters with high ORP, tetravalent lead (Pb(IV)) compounds, such as PbO₂, can form a scale on the pipes (Boyd, et al., 2008). The reaction time and concentration of chlorine residual needed to form tetravalent lead scales is unique to each system and is influenced by natural organic matter (NOM) and alkalinity (Boyd, et al., 2008), in addition to pH. Tetravalent lead scales are very effective at reducing lead corrosion in the system when the appropriate water chemistry is maintained. However, when the water chemistry is modified, such as if the ORP is lowered (e.g., due to a low free chlorine residual) and/or pH is lowered, the scales will destabilize relatively

quickly and result in release of particulate lead. Without the presence of a high ORP or the addition of orthophosphate to form highly insoluble lead-phosphate mineral phases, carbonate scales such as hydrocerussite and cerussite are the dominant mineral phases that will form and these mineral phases are more soluble, particularly at the lower pH values existing in the Newark distribution system. This appears to be the situation in both the North and South Wards according to the scales analyzed by the EPA and the results of the sequential sampling. The situation appears to be occurring to a greater degree in the South Ward.

When redox conditions change, the highly insoluble PbO_2 reduces back to the more soluble Pb(II) if the ORP is not maintained, thereby increasing soluble lead levels in the water. This can happen if the disinfectant changes, such as from free chlorine to chloramines, or if there is a loss of chlorine residual (DeSantis, Conversion of Lead Corrosion Scale Under Changing Redox Conditions, 2017). Newark does not have historic ORP data. However, chlorine residual data at the Rechlorination Station are presented in Section 3.3.2. The data show a recent slight drop in chlorine residual from a range of 1.1 to 1.3 mg/L to an average of approximately 1.0 mg/L which is not a significant enough decrease in ORP to reduce PbO_2 scales back to the more soluble Pb(II) scales based on that one factor alone.

Plattnerite (PbO_2) scales can also change and reduce back to more soluble Pb(II) if there is a reduction in pH in the system. Historic pH values presented in Section 3.3.1 indicate that pH was reduced appreciably in 2016. Before that time, pH was maintained above 8.0. It is possible that the ORP was high enough at that pH to form and maintain PbO_2 scales in Newark's system. This is discussed in more detail in Section 6.

The two EPA scale analysis reports provided in Appendix A (EPA, 2018) noted that the Newark plattnerite scales have a more complex internal structure compared to plattnerite-dominated scales they have observed from distribution systems with a history of stable water quality. With Newark's variability in water quality over time, the plattnerite scale may currently be unstable, resulting in particulate lead release. The results of the lead sequential sampling in Section 4 indicating high particulate lead concentrations further strengthens this presumption.

5.3.3 Additional Scale Analyses

Additional scale analyses are recommended to be performed in other wards in Newark, including one lead pipe from the West Ward and one lead pipe from the Central Ward, which are supplied mainly by water from Pequannock. Scale analyses are to be analyzed from lead service lines supplied water from Wanaque, which contains orthophosphate, under a separate memorandum. This will provide a useful comparison with the Pequannock system.

Section 6

Potential Causes of Elevated Lead Levels

6.1 Overview

Every water system is unique, based on its water chemistry and treatment history. Although there is not complete certainty as to the cause of the recent increase in lead levels in Newark, there are many factors that potentially contributed to it. This section reviews these factors in an attempt to explain the increase in lead in Newark's distribution system in 2017 and 2018.

The following factors may have influenced the 2017-2018 elevated lead levels in Newark's distribution system and are described in more detail in Sections 6.2 and 6.3 of this report:

- Decrease in pH in the distribution system
- LCR compliance sampling

The following factors may have played a role, but are less likely to have contributed significantly to the 2017-2018 elevated lead levels:

- **ORP.** Changes in ORP in the distribution system are unlikely to have contributed to the recent increase in elevated lead levels based on the 2005 to 2018 chlorine residual levels at the Valley Road Rechlorination Station, which were fairly consistent on a monthly average basis.
- **Silicate.** Based on all available information for this project, it seems that sodium silicate is acting as a pH adjustment chemical and not as a corrosion inhibitor. Therefore, the reported reduction in sodium silicate dosing since the late 1990s impacts lead levels insofar as it correlates with reduced pH leaving the Pequannock WTP. Although a silica layer was found on the LSLs analyzed by the EPA, the lead results in the sequential sampling indicate that the silica layer is not effectively preventing soluble lead release. It is believed that sodium silicate is not currently providing a beneficial impact on lead levels in the distribution system beyond pH adjustment. The impact of pH from reducing the sodium silicate dose is addressed in Section 6.2.
- **CSMR.** A CSMR of approximately 3 (range 1.9 – 3.8) has been consistent in the Newark system for at least 24 years and is unlikely to be contributing significantly to the recent increase in elevated lead levels. There is not enough data to accurately determine the CSMR in 2015 and 2016. The CSMR was calculated to be 5.1 from data collected in October 2017, as was shown in **Table 3-2**. This was a greater level than observed for the 20+ previous years, and results from an unusually low sulfate value, which appears to be an outlier.

6.2 Decrease in pH in the Distribution System

As presented in Section 3.3.1, the pH at the Valley Road Rechlorination Station, just upstream of the distribution system, fluctuated significantly between 2005 and 2018. As shown in **Figure 3-**

18, the average pH range was 7.6 to 8.0 from 2005 to 2012, with a few sustained periods above 8.0. After 2012, the pH decreased to an average range of 7.5 to 7.7, and then briefly returned to an average of 8.0 in 2015 for a few months. Starting in 2016, the pH decreased to the current average of approximately 7.0. **Figure 3-17** shows the pH leaving the Pequannock WTP over an even longer history, where the pH decrease is apparent. The graph shows a pH range of 8.5 to 9.0 in the 1990s, decreasing to a range of 8.0 to 8.3 until 2013, and then to the recent average of approximately 7.1.

The reason for the decrease in pH is primarily due to Newark's efforts to reduce disinfection byproduct formation and improve primary disinfection at the Pequannock WTP. Previous operational difficulties with the quicklime system that was removed in 2017, the new hydrated lime system and the sodium silicate feed system discussed in Section 2, may have also temporarily contributed to the decrease in pH, however, it is believed that the main driver for the lower pH was to meet disinfection requirements.

The pH within the distribution system has a major impact on corrosion control. In systems without orthophosphate, control of lead relies on the formation of carbonate scales or tetravalent lead (Pb(IV)) scales. For carbonate scales, such as cerussite and hydrocerussite, pH and alkalinity are critical parameters in their formation. For tetravalent lead, scale formation is based on pH, ORP and the concentration of natural organic material. Both types of scales are found in Newark's distribution system. The following section describes the impact of reduced pH on these two types of lead scales.

6.2.1 pH Impacts on Pb(II) Scales

Section 7 discusses the solubility of lead carbonate mineral scales and provides an estimation of the required pH for carbonate scales alone to reduce lead levels substantially in Newark's distribution system. As presented in Section 7, the pH would need to be over 9.0 to theoretically reduce soluble lead in Newark's system using Pb(II) carbonate scales.

Based on corrosion chemistry and solubility modeling, a pH of 8.0 or less would not reduce soluble Pb(II) significantly enough to be in compliance with the LCR. Since Newark was in compliance with the LCR from 1998 to 2015, when the pH ranged from 7.6 to 8.0 during the majority of that period, it is possible that tetravalent lead (Pb(IV)) or plattnerite scales were more prominent during that time, providing some degree of protection against lead release.

6.2.2 pH Impacts on Pb(IV) Scales

Plattnerite is more likely to form in systems with higher pH values, high oxidative conditions (i.e., high ORP) and low organic matter conditions. Plattnerite is extremely insoluble and, if the scale is stable with consistent water quality, would be more protective against lead being released than Pb(II) scales (Boyd, et al., 2008).

ORP is a quantitative measure of the state of oxidation in water and varies with pH, temperature, and dissolved inorganic carbon (DIC), but is primarily driven by the type and concentration of disinfectant in the water (e.g., chlorine or chloramines). ORP is measured using a platinum reference electrode and reported in units of volts (V), and then normalized with respect to a standard hydrogen electrode and reported as electric potential (Eh).

Figure 6-1 illustrates an Eh-pH (Pourbaix) diagram for system conditions with a dissolved DIC level of 8.5 mg/L as C, in the range of what is seen in Newark's system. Eh-pH diagrams, also called predominance area diagrams, are based on theory, and the boundaries of the species can vary, depending upon the data used to construct the diagram. In **Figure 6-1**, Eh represents ORP, which correlates with chlorine residual. At a sufficiently high ORP, plattnerite (PbO_2) would form in this water across a wide range of pH conditions, with formation occurring more dominantly at higher pH levels. As shown on **Figure 6-1**, plattnerite is in the dominant phase when operating at historical pH values of 8.0 and above at high ORP values. By lowering pH to 7.0, predicted dominance shifts towards PbCO_3 and Pb^{2+} , this leading to PbO_2 instability. It should be noted that ORP data collection is not a regulatory requirement and historic values are not available for the Newark system.

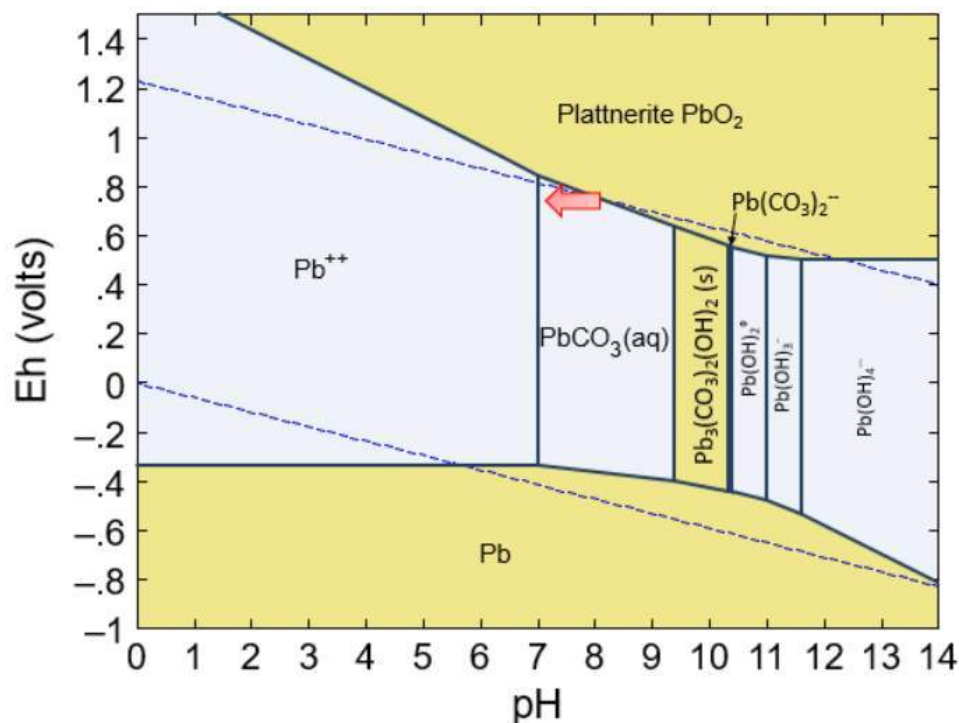


Figure 6-1 – Potential-pH (Pourbaix) Diagram for Water with DIC = 8.5 mg C/L

In systems where there has been a known increase in lead at the tap resulting from destabilization of Pb(IV) scales, it is typically a result of a decrease in ORP, such as changing the disinfectant from free chlorine to chloramines. As can be seen in **Figure 6-1**, decreasing ORP (Eh) would convert PbO_2 , an extremely insoluble compound, to the more soluble Pb(II) carbonate compounds, resulting in lead release into the water.

Additionally, if the ORP is stable but the pH decreases, then conditions amenable to PbO_2 dominance change and cause previously stable PbO_2 to become unstable and convert to more soluble Pb(II) carbonate compounds and soluble Pb (Pb^{++}). This is represented by the red arrow shown on **Figure 6-1**. If this situation occurs, one would expect to see elevated levels of soluble lead during sequential sampling, as well as insoluble (particulate) lead as a result of the scale becoming destabilized. As presented in Section 4, the results of the sequential sampling in

Newark showed elevated levels of both soluble and particulate lead, indicating that conversion from PbO_2 to Pb(II) scales and Pb^{++} may currently be taking place at the reduced pH of Newark's distribution system.

Because both Pb(II) scales and Pb(IV) scales were found on Newark's LSLs and reducing pH adversely affects the solubility of both types of scales, **the reduction in pH in the Newark distribution system is likely the main cause for the 2017 and 2018 elevated lead levels.** Raising the pH to levels that will provide the desirable chemistry for these scales to re-stabilize and control lead release will risk simultaneous compliance with primary disinfection and disinfection byproduct regulations. Simply returning to the corrosion control strategy Newark had in the 1990s and early 2000s to comply with LCR is no longer considered a viable option unless corrective actions are taken to achieve primary disinfection and disinfection byproduct compliance (e.g., alternate disinfectant, removal of disinfection byproduct precursors, etc.).

6.2.3 Sodium Silicate and pH

The primary corrosion protection offered by sodium silicate is the increase in pH that comes from the addition of the chemical, particularly in low alkalinity waters (AWWA, 2017). The 1994 Corrosion Study recommended a starting dose of 24 mg/L as SiO_2 (or 72 mg/L as sodium silicate) and a maintenance dose of 8 mg/L as SiO_2 (or 24 mg/L as sodium silicate), which resulted in a finished water pH between 8.4 and 9.0 (Newark, 1994). If the study recommendations were implemented in the mid-1990s, this would explain the pH levels of over 8.5 in the Pequannock WTP finished water as shown in **Figure 3-17**. The current silicate dosing of approximately 12 to 15 mg/L (or 3.5 to 4.4 mg/L as SiO_2) may partially explain the decrease in pH seen over time as shown in **Figure 3-17**.

As corrosion control chemistry transitions occur slowly over time, it cannot be determined exactly when the lead levels started to increase. However, trends of increased lead levels in the compliance samples, under the LCR, aid in determining the effectiveness of corrosion control. As mentioned in Section 6.2.2, it would not be advisable at this time for Newark to increase the sodium silicate dose to the levels recommended in the 1994 corrosion optimization study, thereby increasing pH (8.4-9.0), unless a strategy for compliance with disinfection and disinfection byproduct regulations is developed and unless the solution was long-term.

6.3 LCR Compliance Sampling

It is well-known that LCR compliance sampling does not always reflect actual lead levels that customers are exposed to and does not always confirm if CCT is optimized. In the case of Newark, the following LCR compliance sampling factors could have affected the early detection of an ongoing or growing lead problem:

- First-draw sample volume required by the LCR
- Error resulting from customer collection of samples
- Accuracy of inventory and confirmation of sample sites
- Proportional mix of Pequannock and Wanaque sampling sites

These are described in more detail below.

6.3.1 First-Draw Sample Volume Required by the LCR

As is the case in many water systems, the first-draw one-liter (L) sample after a 6+ hour stagnation period, as required by the LCR, may not represent the highest levels of lead in the service line. This sample only represents the water closest to the faucet (typically the first 10-20 feet of the premise plumbing), whereas the stagnant water in the lead piping may not be drawn until much later, depending on the layout of the home plumbing.

As described in Section 4, two lead profiles were generated by performing sequential sampling at two sites, Site A (South Ward) and Site B (North Ward). The first draw sample (of 500 mL) for Site A resulted in 93.1 µg/L total lead; however, lead levels peaked at 399 µg/L in the 15th sample (at a cumulative volume of water of 7.5 L). The lead reached the highest value where the volume of water represents the location of the lead service line. For Site B, the first draw sample (of 500 mL) resulted in 17.5 µg/L of total lead, whereas the lead results peaked with a value of 174 µg/L in the 4th sample (at a cumulative volume of 2.0 L). The lead reached the highest value in the location of the galvanized piping.

It is clear from the sequential sampling that first-draw samples are not likely to capture the highest lead sample.

6.3.2 Error Resulting from Customer Collection of Samples

As per the LCR, the customer is responsible for collecting a sample after 6+ hour stagnation period. This could result in variability of the amount of lead in the sample. Because customers may collect each sample after different stagnation periods or may not sample exactly the same way each time, lead samples could easily show significant variability. Further, the number of required samples has increased over the years from 50 samples every 3 years to 100 samples twice a year. By increasing the number of samples, the potential for variability increases.

6.3.3 Accuracy of Inventory and Confirmation of Sample Sites

Upon review of the City of Newark's historic compliance sampling over the last 20+ years, it is not clear if all homes selected for sampling in some years that were confirmed as sites with lead service lines (i.e. Tier 1 sample sites). The LCR requirements for the sampling pool have been clarified over time and the original Rule did not establish clear guidelines for the site selections. It has not been confirmed if the historic sample sites were Tier 1 sites at the time of each sampling round. Newark has confirmed that their sampling pool in 2017 and 2018 contains only Tier 1 sites.

6.3.4 Proportional Mix of Pequannock and Wanaque Sampling Sites

Upon review of the City of Newark's historic compliance sampling results, it was observed that the compliance sampling program did not proportionally represent both Pequannock-supplied areas and Wanaque-supplied areas in each sampling round. For example, in some sampling rounds, only areas served by Pequannock were sampled, and in other rounds, only areas served by Wanaque were sampled. This would influence the ability to identify clear data trends, such as increasing lead levels in the system.

Section 7

Desktop Corrosion Control Evaluation

This section presents an overview of available corrosion control treatment (CCT) methods for lead. In addition, this section summarizes theoretical lead solubility modeling of carbonate and phosphate-based chemistry.

7.1 Theoretical Lead Solubility Modeling

The 1991 Lead and Copper Rule (and subsequent revisions) stipulates that public water systems evaluate the effectiveness of each of the following treatments (or, if appropriate, combinations of the following treatments) to identify the optimal corrosion control treatment for that system:

- (i) Alkalinity and pH adjustment;
- (ii) Calcium hardness adjustment; and
- (iii) The addition of a phosphate or silicate-based corrosion inhibitor at a concentration enough to maintain an effective residual concentration in all test tap samples.

Guidance manuals to support implementation of the LCR requirements were developed by USEPA initially in 1997, revised in 2003, and most recently revised in 2016 (US Environmental Protection Agency, 1997).

Subsequent to the promulgation of the LCR and designation of CCT methods, research and full-scale system experience identified that plattnerite (PbO_2), an insoluble Pb(IV) mineral, can form under certain highly oxidative conditions found in distribution systems. Pb(IV) was discovered in the Newark system, along with Pb(II) mineral phases, as reported in Section 5. Pb(II) is discussed in Section 7.1.2 below. Pb(IV) is discussed in detail in Sections 5 and 6 of this report.

7.1.1 Calcium Hardness Adjustment

Since the time of promulgation of the LCR, it has been recognized that calcium hardness adjustment is not an effective form of corrosion control as research has shown that calcium carbonate films only rarely form on lead and copper pipe. As such, calcium hardness is not considered in this report.

7.1.2 Alkalinity and pH Adjustment

Changing the alkalinity and pH causes the formation of insoluble lead/hydroxide/carbonate compounds on the interior wall of water pipes. This process approach binds the lead into complex mineral films of limited solubility, thereby reducing dissolved lead concentrations. In raising the pH, the hydroxide (OH^-) and carbonate (CO_3^{2-}) concentrations are increased. These ions then bind with the lead to decrease lead solubility. In low alkalinity waters with a pH range of 9 to 10, it is generally anticipated that the following insoluble Pb(II) carbonate mineral phases will form:

- Cerussite (PbCO_3) (simple lead carbonate)
- Hydrocerussite ($\text{Pb}_3(\text{CO}_3)_2(\text{OH})_2$), or
- Plumbonacrite ($\text{Pb}_{10}(\text{CO}_3)_6(\text{OH})_6\text{O}$)

7.1.3 Phosphate-based Corrosion Inhibitors

Phosphate-based corrosion inhibitors have been widely used to control lead and copper release. Within the general classification of phosphate compounds, there are two primary types – **orthophosphates** and **polyphosphates**. There are also products termed **blended phosphates** that consist of blends in various proportions of ortho- and poly-phosphates. Orthophosphate inhibitors form relatively insoluble compounds with Pb(II) which, in turn, render the lead relatively immobile. This occurs through the reaction of lead with the orthophosphate to form very insoluble compounds such as hydroxypyromorphite ($\text{Pb}_5(\text{PO}_4)_3\text{OH}$) and tertiary lead orthophosphate ($\text{Pb}_3(\text{PO}_4)_2$).

The literature and actual operating experience establish that orthophosphate (not polyphosphate) is the active form of the corrosion inhibitor that effectively reduces lead solubility. Reiber et al., states, “Almost all studies agree that orthophosphate is, within a narrow pH window, an effective corrosion inhibitor for both lead and copper surfaces. There is little evidence to suggest that pure polyphosphates play a role in corrosion inhibition.” (Reiber, 1991)

Several factors govern the effectiveness of orthophosphate addition – namely the pH, dissolved inorganic carbon (DIC), and orthophosphate dosage. The optimum pH for lead solubility reduction by orthophosphate depends on the background DIC/alkalinity of the water. Solubility models predict that the maximum benefit from orthophosphate inhibitors will occur in the lowest alkalinity waters (Reiber, 1991).

7.1.4 Silicate-based Corrosion Inhibitors

Silicate-based corrosion inhibitors are limited in terms of the information available on their use and effectiveness. Sodium silicate (Na_2SiO_3) is used primarily as a sequestering agent for the control of iron and manganese, but has been used with varying degrees of success in controlling lead and copper corrosion.

Little research and field information are available to prove the effectiveness of silicate-based inhibitors for lead control. The limited work that has been done has shown that a relatively high concentration of silicate is needed (around 20 mg SiO_2/L), and that it may take months to see any reduction in lead concentrations (American Water Works Research Foundation and DVGW-Technologiezentrum Wasser, 1996). The mechanism by which sodium silicate works to prevent lead from leaching into the water is not known. Speculation ranges from the formation of a passivating compound on the pipe wall to adsorption of lead ions (as well as other ions such as iron and manganese) to the surface of a silicate film on the pipe wall (American Water Works Research Foundation and DVGW-Technologiezentrum Wasser, 1996).

The inhibitory effects on corrosion scale formation and surface roughness of pipe materials common to drinking water distribution systems with and without exposure to phosphorus- and silicon-based inhibitors were investigated using X-ray photoelectron spectroscopy (XPS) and

profilometry in a 2008 research project. (Water Research Foundation, 2008). XPS was used to identify various forms of lead corrosion scales to determine the controlling solid phase(s). No Pb-Si complexes were found in the scales when silicates were used. The researchers also noted that, after a thorough review of lead complex formation literature, there was no evidence to suggest complexation of lead and silica.

Notwithstanding the unknown protection mechanism, it is reported that for passivation of lead, the required dose of sodium silicate solution is typically much higher (20–30 mg/L as sodium silicate) than that of the phosphate-based inhibitors (1–2 mg/L as P) (AWWA, 2017).

Because silicates are highly alkaline, the primary corrosion protection offered by silicates is believed to be the increase in pH that comes from the addition of the chemical, particularly in low alkalinity waters. Increased pH is beneficial as it promotes formation of low solubility lead carbonate mineral phases as discussed above. However, it would likely be more economical to increase pH using standard chemicals such as lime or sodium hydroxide.

The WRF study on corrosion inhibitors detected silica in the scale of 50% of the coupons exposed to a silicate inhibitor (Water Research Foundation, 2008). The scale on all coupons exposed to the silicate inhibitor appeared denser than other scales formed in the presence of phosphate or carbonate inhibition. The study noted that an advantage of silicate addition may be in the promotion of a denser amorphous silica layer.

The silicate in sodium silicate solutions carries a negative charge and will, in theory, migrate to anodic areas where it can react with metallic ions. One manufacturer of sodium silicate (PQ Corporation) reported that monomeric silica represented by SiO_3^{-2} is adsorbed onto pipe surfaces at anodic areas, forming a thin monomolecular film on the interior of the pipe, preventing further corrosion at the anode (Water Research Foundation, 2008). This work included microscopic and X-ray examination of the film formed at the metal surface, which showed it had two layers, with most of the silica in the surface layer adjacent to the water. This work also reported that naturally occurring silica in the form of SiO_2 probably reacts with cations in bulk water and may not be effective in reacting with pipe surfaces.

As discussed in Section 5, a silica crust (SiO_2) was found on all three lead service lines examined from the Newark system. The silica crust was found to be relatively porous and therefore not acting as an effective barrier against the outward flux of lead released from the pipe as the passivating lead layers (mainly plattnerite and hydrocerussite) were found behind the silica crust.

In summary, no evidence has been found to demonstrate that silicates form insoluble (or low solubility) phases with lead to immobilize lead into protective pipe scales. The likely benefit of silicates is the resulting boost in pH, which promotes the formation of lead carbonate scales, or in the formation of a dense silica scale to form a barrier against lead release.

7.2 Theoretical Lead Solubility Modeling

Equilibrium solubility models can be useful to evaluate corrosion characteristics of water and to predict changes in those characteristics with changes in water quality conditions and treatment. However, solubility models are dependent upon the accuracy of the *characterization of the*

solids and complexes considered, the accuracy of the thermodynamic constants used for the various chemical reactions, and do not take into account important aspects of kinetics, interaction with organic materials or tuberculation/ corrosion products, and post-treatment deposition of various scales (such as compounds of iron, calcium and manganese). The most widely-used solubility models are based on Pb(II) mineral phases – either carbonate or phosphate – controlling lead solubility.

As presented in Section 5, the scale analyses conducted by the EPA revealed that Pb(II) chemistry is only partially applicable to Newark's current conditions, as Pb(IV) solids are also present in the pipe scales. All three locations analyzed showed both Pb(II) and Pb(IV) scale deposits, with the outermost layers being primarily hydrocerussite (Pb(II)), with cerussite (Pb(II)) and plattnerite (Pb(IV)) also present.

Work by Schock and Gardels in 1983 identified a discrepancy in lead solubility data when compared with predicted solubility curves. At the time, it was believed that the discrepancy was a result of experimental and theoretical errors and to the possible presence of Pb(IV) compounds in chlorinated waters. Subsequent research by Schock, published in 1990 and 1996, indicated that the discrepancy was likely due to the potential formation of Pb(IV) compounds in drinking water distribution systems (Boyd, et al., 2008) which are not represented by the Pb(II) solubility models.

CDM Smith often uses the Water!Pro Corrosion Control and Treatment Process Analysis Program (Water!Pro), supplemented by published lead solubility diagrams (American Water Works Research Foundation and DVGW-Technologiezentrum Wasser, 1996)), to evaluate theoretical lead solubility and effectiveness of alternative corrosion control treatment options. As with most other equilibrium solubility models, Water!Pro is based on Pb(II) solids controlling lead solubility.

For the Newark desktop analysis, the Water!Pro model was used as a guide to provide information to supplement the decision-making process, recognizing the limitations of its applicability given the scale analysis findings of mixed Pb(II) and Pb(IV) mineral phases. The model analysis is presented herein to evaluate alternatives to reduce lead solubility based on anticipated future conditions being dominated by Pb(II) as the controlling lead species. As discussed in this report, it is not viable to attempt to maintain Pb(IV) as the controlling oxidation state given the current challenges with achieving simultaneous compliance with the Stage 2 Disinfection Byproducts Rule.

The model analysis in no way predicts the transition from Pb(IV) to Pb(II), or the reduction in lead solubility from current conditions to the future proposed scenarios, due to the limitations of the model. It is also important to note that the theoretical Pb(II) solubility values predicted by the model are **not** lead concentrations that would be measured at customers' taps. In practice, lead levels at the customers' taps are often lower than predicted. In the field, sampling rarely occurs under ideal conditions of true chemical equilibrium as assumed by the solubility models. In addition, some water constituents that may affect lead corrosion in drinking water may not be adequately represented in the model, as discussed above.

7.3 Model Inputs

The historic water quality and chemical usage for Newark is presented in Section 3. **Table 7-1** below summarizes the key water quality parameters, by season, that were used as input for the Water!Pro model.

Table 7-1 – Model Input of Seasonal Water Quality Parameters

Source Water	Newark - Pequannock Reservoir			
Scenario #	1	2	3	4
Season	Summer (Jun-Aug)	Fall (Sept-Nov)	Winter (Dec-Feb)	Spring (Mar-May)
Water Quality Input				
TDS, mg/L ^[1]	118.0	116.0	109.3	118.0
Calcium, mg/L Ca ²⁺	10.4	10.0	9.5	9.5
Total Alkalinity, mg/L as CaCO ₃	23.8	24.6	21.7	19.5
pH	6.7	6.6	6.6	6.5
Field Water Temperature, deg. C	21.8	13.8	6.5	13.3
Cl ⁻ , mg/L ^[2]	30.8	34.7	37.1	33.6
SO ₄ ²⁻ , mg-/L ^[3]	10.7	10.1	11.5	11.3
Mg ²⁺ ^[4] , mg/L	4.4	4.6	4.4	4.1

^[1] 9 monthly averages from the 'Optimal Corrosion Control Treatment Recommendations Dec 2017' report.

^[2] 16 samples from 1994-2017 from NJDEP Drinking Water Watch

^[3] 22 samples from 1994-2017 from NJDEP Drinking Water Watch

^[4] 17 samples from 1994-2017 from NJDEP Drinking Water Watch – Delivered Water

Table 7-2 summarizes the chemical additives used in the Water!Pro model, based on seasonal averages, from the information provided by the Newark plant staff. Sodium hypochlorite was used in the model instead of chlorine gas, as the City of Newark will be switching their current feed system to a sodium hypochlorite feed system in the near future.

Table 7-2 – Model Input of Seasonal Chemical Addition Parameters

Source Water	Newark – Pequannock WTP			
Scenario #	1	2	3	4
Season	Summer (Jun-Aug)	Fall (Sept-Nov)	Winter (Dec-Feb)	Spring (Mar-May)
Chemical Addition Input				
100% Hydrated Lime (Ca(OH) ₂), mg/L	3.3	4.2	3.2	2.7
Clarion (0.5%Acid Alum*14.3H ₂ O), mg/L	9.0	9.8	9.9	9.4
Sodium Hypochlorite (NaOCl), mg/L as Cl ₂	3.5	3.1	2.7	2.3
PACI (12.2% Al, 70% Basicity), mg/L	1.9	2.5	1.8	1.8

7.4 Lead Solubility – Existing Conditions

As noted above, the current Newark conditions cannot be modeled with the Water!Pro model because the model is based on Pb(II) minerals (either carbonate or phosphate) being the controlling lead phase whereas both Pb(II) and Pb(IV) were found in the Newark system scales. However, knowing that it is impractical to maintain the Pb(IV) scales to control lead, any future corrosion control treatment will involve either carbonate or phosphate chemistry. As such, the model was utilized to illustrate the **theoretical** lead solubility for various carbonate and phosphate conditions.

The initial step was to estimate the theoretical lead solubility under current conditions, assuming only Pb(II) carbonate solids are controlling lead release. This was then compared to the theoretical lead solubility for: (1) optimized pH/alkalinity conditions, and (2) with the use of orthophosphate.

Newark's system operated with an average finished water alkalinity that ranged from 22.0 mg/L to 24.9 mg/L from 2015-2018, with an average of 23.5 mg/L as CaCO₃. From 2015-2018, the pH ranged from 6.9 to 7.3. The dissolved inorganic carbon (DIC) level was calculated as 8.2 to 9.7 mg/L as C.

The theoretical lead solubility of Newark's current system is presented in **Table 7-3**, and seasonally ranges from 207 µg/L to 437 µg/L of lead.

Table 7-3 – Theoretical Lead [Pb(II)] Solubility by Season (with Sodium Hypochlorite)

Season	pH 2018 operating range	Theoretical Lead [Pb(II)] Solubility (µg/L)
Summer	6.72 – 7.3	.437 – 259
Fall	6.72 – 7.3	355 – 209
Winter	6.72 – 7.3	352 – 207
Spring	6.72 – 7.3	402 – 209

These values were then used as a “baseline” for comparison to alternatives aimed at reducing theoretical Pb(II) solubility, and thus achieving lower lead levels at the tap.

7.5 Lead Solubility – Modified CCT Alternatives

Several alternatives were evaluated to determine their impact on the theoretical Pb(II) solubility including:

- Increased finished water pH
- Addition of orthophosphate

The following discussion summarizes the results.

7.5.1 Increased Finished Water pH

Both lime and sodium hydroxide were evaluated for pH adjustment. Both chemicals provided the same reduction in theoretical lead solubility, therefore only the results for lime are presented

here. **Figure 7-1** demonstrates the theoretical Pb(II) solubility for the summer water quality parameters as pH increases. Similar results were observed under all seasonal conditions. As shown in **Figure 7-1**, the theoretical Pb(II) solubility significantly decreases as pH is increased to approximately 9.5. A pH level of about 9.0 – 9.5 would theoretically be needed to optimize carbonate scale formation and maintain dissolved lead levels at acceptable values.

Increasing pH to 9.0 – 9.5 reduces lead solubility, but will likely result in increased disinfection byproduct levels. Newark is currently challenged with compliance of the Stage 2 Disinfectant and Disinfection Byproducts Rule for both trihalomethanes (THMs) and haloacetic acids (HAAs). It is not advisable for Newark to raise the pH to optimize carbonate scale formation at this time with the current treatment processes, open water reservoir, and disinfection chemicals. A more systematic and comprehensive evaluation to control disinfection byproduct formation and achieve effective primary disinfection would be needed.

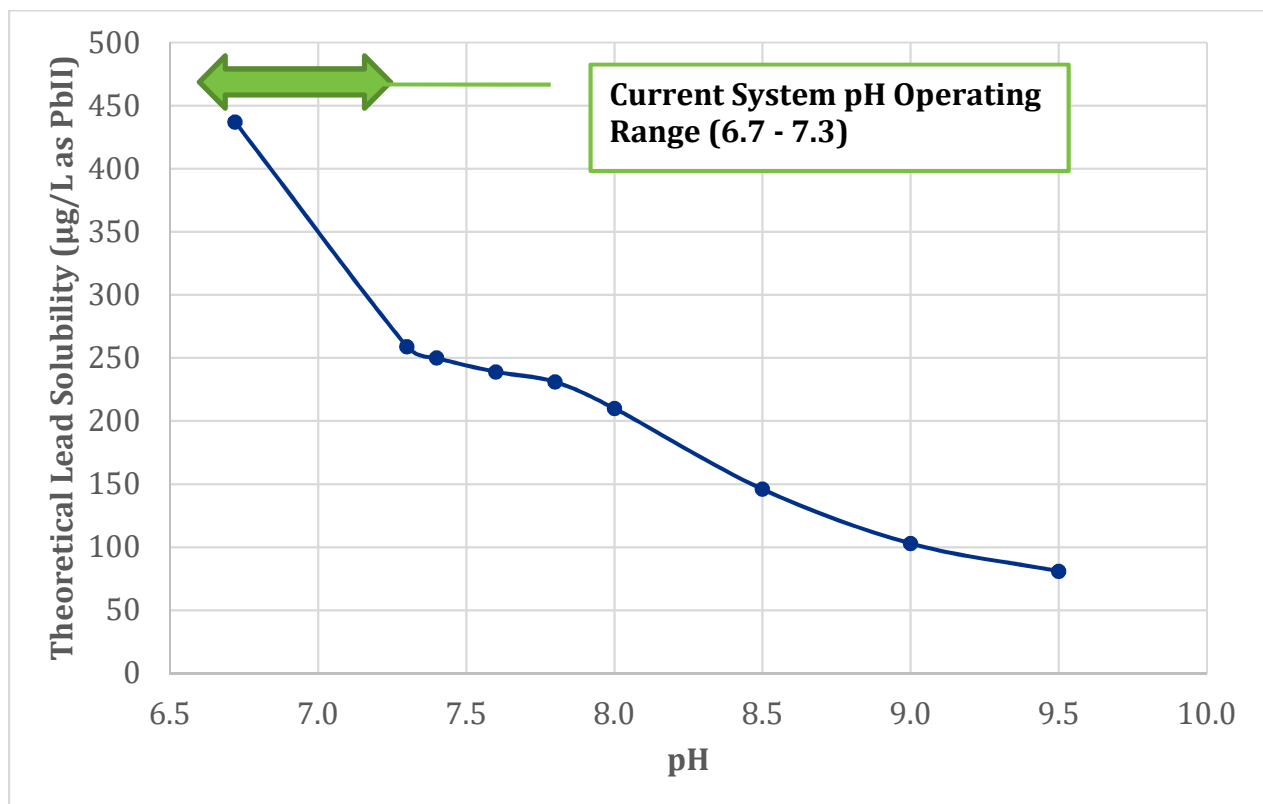


Figure 7-1 – Effect of pH Adjustment on Theoretical Pb(II) Solubility

7.5.2 Addition of Orthophosphate

The use of orthophosphate has been a successful approach for minimizing corrosion of lead-containing materials (USEPA, 1993). Solubility models and experience indicate that the optimal pH for orthophosphate scale formation is between 7.2 and 7.8 (US Environmental Protection Agency, 2016).

Using the seasonal water quality data in Table 7.1, theoretical lead solubility values were modeled for various orthophosphate concentrations at the current baseline average pH of 7.1, as well as at

pH of 7.3 and 7.5, to cover the anticipated range of optimal pH conditions. Results at pH 7.8 were theoretically the same as at pH 7.5.

Figure 7-2 presents theoretical lead solubility across a range of orthophosphate dosages (0.5 to 3.5 mg/L as PO₄) and pH levels for summer conditions. Similar results were achieved for all seasonal conditions showing a reduction in lead solubility. Movement from one place on the graph to another with lower lead solubility is expected to result in reduced concentrations of soluble lead in the field.

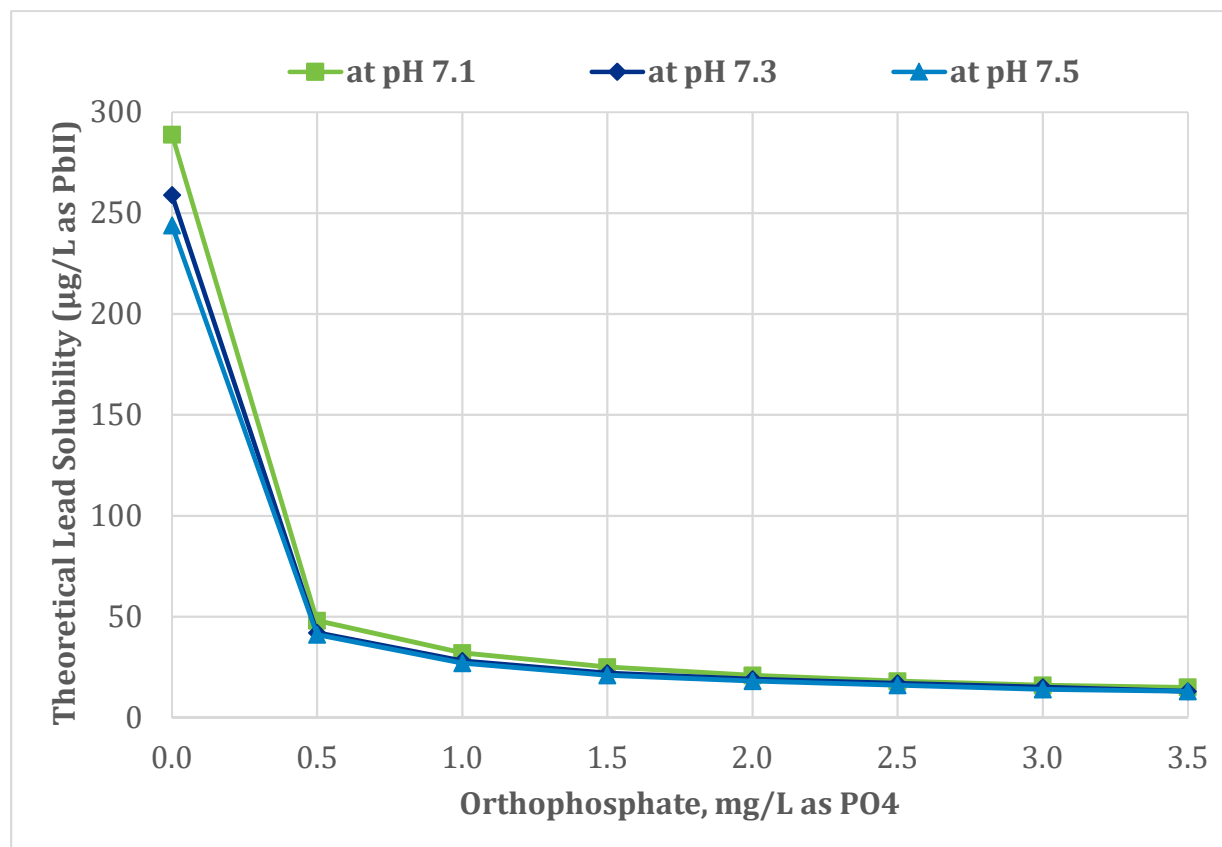


Figure 7-2 – Effect of Orthophosphate on Theoretical Pb(II) Solubility at Varying pH Values in Summer

Overall, the results show that orthophosphate can significantly reduce theoretical lead solubility in the City of Newark's drinking water considering only Pb(II) chemistry. For example, as shown on **Figure 7-2**, at an average pH of 7.3, lead solubility as Pb(II) is theoretically reduced by 83% with the first 0.5 mg/L of orthophosphate as PO₄ and by 89% when orthophosphate is increased to 1.0 mg/L as PO₄.

Although benefits to reducing lead solubility continue with increasing PO₄ dose, as demonstrated in **Figure 7-2**, the incremental reduction in theoretical Pb(II) solubility becomes less significant with dosages greater than 1.0 mg/L as PO₄. However, this does not account for particulate lead that may enter the system as a result of the instability of the legacy Pb(IV) and Pb(II) carbonate scales. It is not known what level of orthophosphate addition would be required to control the

distribution and mobility of lead particles. However, full-scale experience from other systems with lead release conditions has shown that orthophosphate doses in excess of that theoretically required were necessary. The addition of orthophosphate can readily lower dissolved lead levels, but total lead concentrations can persist at elevated levels for a longer period of time (Giammar, 2017). In comparing the pH adjustment alternative to the orthophosphate option for controlling soluble Pb(II) lead, the theoretical dissolved Pb(II) concentration with pH adjustment to 9.5 without orthophosphate addition is almost three times higher than that with 1.0 mg/L of orthophosphate as PO_4 at a pH of 7.3. This does not account for any impact of legacy Pb(IV) solids in the system. It is important to recognize that theoretical lead solubility modeling only considers Pb(II) mineral phases to control soluble lead. Elevated lead concentrations at the tap can occur due to the presence of insoluble lead particles dislodged from lead pipe, solder or brass plumbing fixtures. Elevated lead concentrations due to particulate lead cannot be predicted.

As discussed in Section 7.1.4, the current practice of sodium silicate addition provides an increase in pH, which may be more economically achieved by the addition of a less costly alkaline chemical such as lime or sodium hydroxide. Because the Pequannock WTP currently uses lime, the amount of lime needed to increase pH without the use of sodium silicate was examined. It is recognized that the existing lime system has limitations that would need to be addressed should sodium silicate addition be discontinued in the future.

Table 7-4 presents an estimate of the amount of hydrated lime needed to accompany various amounts of added orthophosphate (without the addition of sodium silicate) to achieve finished water pH conditions of 7.2 and 7.4. The addition of lime increases with the addition of orthophosphate since orthophosphate is an acid.

Table 7-4 – Estimated Theoretical Lime Dose to Maintain Desired pH for Orthophosphate

Season	Dose (mg/L as PO_4)	Hydrated Lime Dose Needed to Achieve Target pH (without Silicate) (mg/L)	
		7.2 pH	7.4 pH
Summer	0.5	7.3	8.4
	1.0	7.6	8.8
	2.0	8.3	9.7
	3.0	9.2	11.1
Fall	0.5	10.5	12.1
	1.0	10.8	12.4
	2.0	11.6	13.3
	3.0	12.4	14.2
Winter	0.5	10.7	12.3
	1.0	11.0	12.7
	2.0	11.7	13.5
	3.0	12.4	14.4
Spring	0.5	11.2	12.5
	1.0	11.5	12.9

Season	Dose (mg/L as PO ₄)	Hydrated Lime Dose Needed to Achieve Target pH (without Silicate) (mg/L)	
		7.2 pH	7.4 pH
	2.0	12.2	13.8
	3.0	13.0	14.8

As discussed in **Section 3.3.1**, buffer intensity is more greatly influenced by pH than alkalinity. Waters with a pH outside of the range of 8.0 and 8.5 (including the optimal pH range for orthophosphate of 7.2 to 7.8), even with low DIC, will have higher buffer intensity and should exhibit less variability in pH in the distribution system. **Figure 7-3** shows the impact of pH and alkalinity on buffer intensity for the Pequannock finished water, including the intended pH of 7.4 with the future addition of orthophosphate. As can be seen from the figure, at a constant pH, the buffering capacity remains consistent with increasing alkalinity. However, buffer intensity decreases significantly with increasing pH.

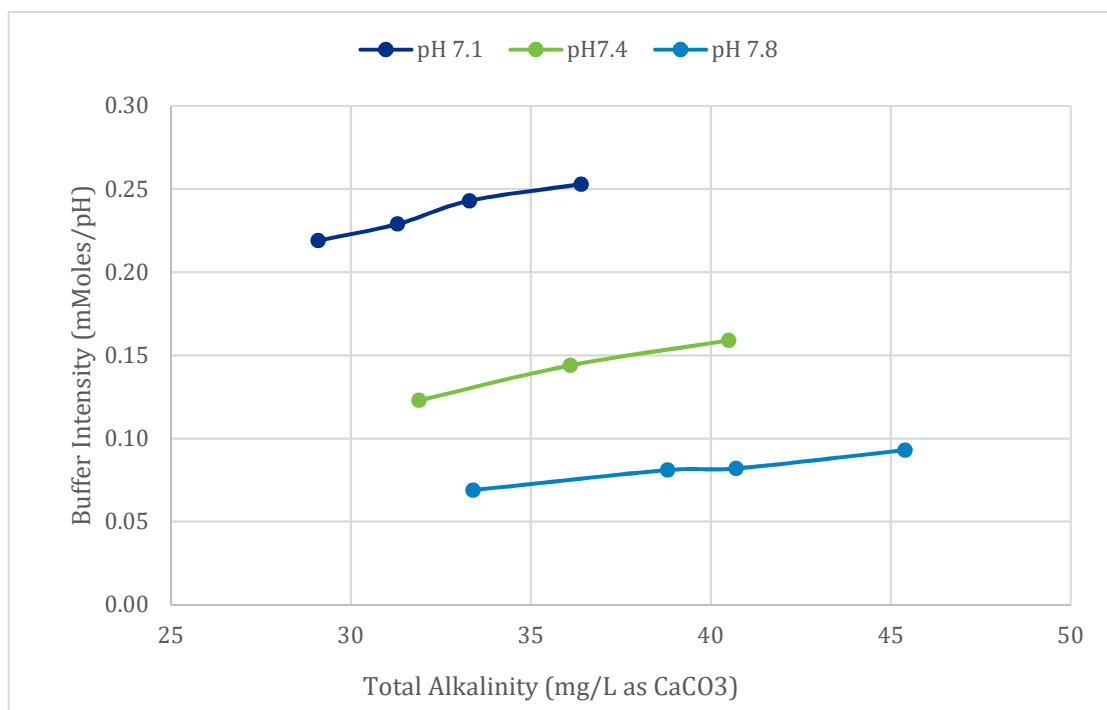


Figure 7-3 – Buffer Intensity as a Function of Alkalinity and pH

7.5.3 Other Alternatives Not Considered

As discussed in Section 7.1, the Lead and Copper Rule, as well as the recent EPA OCCT Evaluation Technical Recommendations for Primary Agencies and Public Water Systems (US Environmental Protection Agency, 2016), identifies three available corrosion control treatment methods: (1) pH/alkalinity/DIC adjustment, (2) phosphate-based corrosion inhibitors, and (3) silicate-based corrosion inhibitors. The evaluation presented above considered the first two methods. As

discussed in Section 7.1, sodium silicate has not been proven to be effective for controlling lead corrosion. Other than its ability to increase pH and encourage formation of carbonate scales at higher pH conditions, it provides only a porous silica crust on the pipe that does not appear to prevent lead release as no Si-Pb crystalline compounds are formed. (see EPA scale analysis in Section 5 and Appendix A). Continuing the use of sodium silicate as the only method for CCT for Newark is not recommended.

Only recently has the formation of the solid phase tetravalent lead (Pb(IV) or PbO₂) been recognized in EPA OCCT Guidance (US Environmental Protection Agency, 2016). Newer research (Schock, 2001) has confirmed that Pb(IV) compounds (e.g., plattnerite) can be the predominant compounds in lead pipe scales under highly oxidative conditions and under low organic matter conditions. (see Pourbaix diagram in Figure 6-1). PbO₂ is extremely insoluble and is very effective in preventing lead from being released to the water. Based on studies performed on systems with known plattnerite scales compared with Pb(II)-based scales, lead levels at the tap and during sequential sampling were lower for the Pb(IV) scales than for the Pb(II) scales (Triantafyllidou, Schock, DeSantis, & White, 2015).

Under high ORP conditions (i.e., high chlorine residual), and in the absence of corrosion inhibitors or other interfering surface deposits, Pb(IV) scales can form on lead pipe surfaces. The predominance of Pb(IV) scales is dependent on ORP (i.e., chlorine residual), pH, and the presence of NOM (Boyd, et al., 2008). As discussed in Section 5.1, the conditions needed for PbO₂ formation may be found in systems that have a high ORP. If the specific water quality conditions are modified, such as decreasing pH and/or reducing chlorine residual which would reduce ORP, the Pb(IV) scale is destabilized and converts back to Pb(II) (Boyd, et al., 2008), and as shown in Figure 6-1. Recent evidence shows that Pb(IV) scales may be more prevalent in systems than previously thought, and may exist at lower chlorine residual levels. The impact pH has on Pb(IV) scales is further discussed in Section 6.2.2 and is illustrated in Figure 6-1.

Because of the importance of pH, maintaining Pb(IV) scales to control lead release is not a realistic option for Newark while simultaneously complying with the Stage 2 Disinfectants and Disinfection Byproducts Rule. In addition, questions remain as to the required chlorine residual that should be maintained in the distribution system and lead service lines for the formation and maintenance of Pb(IV) scales. For this reason, EPA has not adopted Pb(IV) scale formation as an acceptable corrosion control treatment technique at this time.

Section 8

Recommendations

Based on the analysis of the historic lead sampling results presented in Section 2 of the Pequannock and Wanaque water systems, it is clear that the Pequannock system's current CCT has lost its effectiveness while the Wanaque system's CCT has remained effective. The 90th percentile lead level in the Pequannock system slightly exceeded the LCR Lead Action Level of 15 µg/L in 2015 (at 15.8 µg/L) and further increased in 2017 and 2018. The Wanaque system's 90th percentile has remained below the Lead Action Level. Therefore, this section presents recommendations for the City of Newark to improve their corrosion control program in the Pequannock service area only. Both immediate and long-term corrosion control treatment recommendations are provided, as well as interim measures to reduce public health risks until the treatment has time to be effective in reducing lead levels.

The following alternatives were eliminated from further consideration either due to ineffectiveness in reducing lead solubility, or their likely adverse impacts on other water quality goals. The alternatives that were eliminated are discussed in detail in the report sections identified in parentheses below.

- Increase finished water pH to above 9.0 to promote more effective carbonate scale formation (see Section 7)
- Increase finished water pH and ORP for tetravalent lead scale stabilization and maintenance (see Section 5 and Section 6)
- Increase sodium silicate dosing (see Section 6)

The primary recommendation for achieving optimized CCT in Newark's water supply is the addition of an orthophosphate chemical feed system in the Pequannock service area. Details of the proposed system are further discussed in this section of the report. The addition of orthophosphate is anticipated to provide reductions in lead levels without expected adverse impacts on other water quality goals, namely compliance with primary disinfection and disinfection byproduct regulations for Newark and its consecutive systems (i.e. Bloomfield, Belleville, etc.). The benefits and constraints of adding an orthophosphate system in Newark's distribution system are noted as follows:

Benefits of Adding Orthophosphate

- Full-scale experience combined with corrosion control theory indicates orthophosphate will effectively reduce Pb(II) lead solubility in Newark's distribution system with a pH between 7.2 and 7.8.
- Scale analysis performed by the EPA shows a breakdown of the existing tetravalent and carbonate scales. Other systems with similar conditions experienced a significant reduction in total lead within a few months of adding orthophosphate.

- Orthophosphate is a common, proven treatment for lead corrosion control in distribution systems in New Jersey and across the country.
- Orthophosphate will reduce duration of elevated lead levels at the tap resulting from soluble and insoluble lead compared with making no system changes and compared with raising the sodium silicate dose.
- Adding orthophosphate does not require significant water quality modifications, such as a high pH or high chlorine residual, allowing for greater opportunity for simultaneous compliance with primary disinfection and disinfection byproduct regulations.
- Orthophosphate is consistent with the corrosion control treatment in Wanaque system, which will equalize the system during periods of blending between the two systems.
- Orthophosphate is widely available and approved for potable water use.

Secondary Impacts and Possible Constraints of Adding Orthophosphate in Newark

- Unknown potential for increase in insoluble lead during the initial passivation phase as the plattnerite scale continues to be unstable and is replaced with a phosphate-based scale. It is unknown if the orthophosphate will initially exacerbate the particulate issue short-term prior to seeing a reduction in lead levels. Point-of-use filters are recommended to reduce customer exposure to lead during this period.
- Adding orthophosphate will increase phosphorus loading in wastewater.
- Zinc concentrations in wastewater sludge will increase if using zinc orthophosphate.
- Adding orthophosphate will have a potential effect of higher phosphates on some industrial users.
- There is a potential for temporary “dirty” water if the system is not sufficiently flushed prior to implementation.
- There is a potential for white cloudy water with orthophosphate concentrations above 3.2 mg/L as PO_4 . (Tesfai, Constanant, & Reibier, 2006)
- There is a potential for stimulating algae growth if orthophosphate gets into an open body of water, such as the Cedar Grove Reservoir.
- Additional building and security will be needed at the Valley Road Rechlorination Station.
- Possible need for a satellite chemical feed system for the City of Pequannock and any other users upstream of the Valley Road Rechlorination Station.

Wanaque CCT

A separate technical memorandum will be provided with a more detailed evaluation of the Wanaque service area as required by the LCR, including an analysis of areas with potential Pequannock/Wanaque blending, sequential sampling, and pipe scale analyses. The results of the

Wanaque evaluation are not expected to impact the studies and recommendations provided in this report. Any area with blending between the two systems that may have an occasional diluted concentration of orthophosphate in the Wanaque system will benefit from orthophosphate dosing in the Pequannock system to strengthen the CCT further.

8.1 Chemical and Orthophosphate Dosage

Orthophosphate (PO_4), commonly used as a corrosion inhibitor for lead and copper control, was evaluated in a desktop study under four seasonal scenarios and was concluded to be effective in reducing the theoretical lead solubility in all four seasons. The results are presented in Section 7. Orthophosphate reduces lead concentrations through the formation of insoluble Pb(II)-PO_4 mineral phases. (DeSantis, Schock, & Bennett-Stamper, Incorporation of Phosphate into Destablized PbO_2 Pipe Scales, 2012)

For the City of Newark, either phosphoric acid or zinc orthophosphate is recommended. Zinc orthophosphate is a liquid that is available in blends that contain various ratios of zinc to orthophosphate. A zinc orthophosphate blend offers the additional benefits of introducing zinc to the distribution system, which can help reduce corrosion in cement-lined pipes in low alkalinity waters, reduce iron corrosion in unlined pipe, and reduce lead release from brass fittings containing lead. Zinc orthophosphate is more dilute than phosphoric acid, requires twice as much storage volume, and is 3 to 5 times more costly than phosphoric acid for the same active PO_4 dose. In addition, zinc orthophosphate adds zinc into the wastewater sludge, which can impact disposal options for the wastewater treatment facility. Each of these chemicals would be effective for Newark's distribution system as the active ingredient, orthophosphate, is the same.

Although CDM Smith's desktop evaluation presented in Section 7 found that a significant reduction in lead solubility can theoretically be achieved with the first 0.5 mg/L of orthophosphate, the solubility model evaluations cannot account for any soluble lead currently being released into the water as a result of the ongoing destabilization of the PbO_2 scale to soluble Pb(II) . To counteract the current lead release issue without delay, it is recommended that orthophosphate treatment in Newark's distribution system gradually increase to a higher passivation dose prior to settling on a maintenance dose. The 2016 EPA OCCT Guidance Manual states that some systems start with a passivation dose 2 to 3 times higher than the target maintenance dose to build up a protective barrier quickly (US Environmental Protection Agency, 2016). In addition, full-scale experience in other systems with PbO_2 scale destabilization has shown that higher orthophosphate doses (3 to 3.5 mg/L as PO_4) have been able to mitigate the lead release in a relatively short period of time (several months). CDM Smith recommends gradually introducing orthophosphate into the distribution system, starting with a dose of 0.5 mg/L as PO_4 as soon as possible and working up to a passivation dose of 3.0 mg/L as PO_4 . The system will be monitored as discussed later in this Section during the implementation of orthophosphate.

As an example of a similar system, Washington, D.C. started adding orthophosphate in August 2004 in the form of phosphoric acid after it was discovered that a change in disinfectant from free chlorine to chloramines reduced ORP converting PbO_2 , an insoluble tetravalent lead compound, to the more soluble Pb(II) carbonate compounds, resulting in lead release into the water. Washington, D.C. slowly increased the dose of the orthophosphate over a two-week period to 3.5

mg/L as PO₄. At that dose, lead levels in the residential lead service lines reduced from 150 µg/L to 15 µg/L in 8 months based on the sequential sampling profiles. (Giani, Keefer, & Donnelly, 2005)

Although either zinc orthophosphate or phosphoric acid would be appropriate and have the same active chemical, Newark has selected to use zinc orthophosphate to be consistent with the treatment used in the Wanaque water system. Proposed storage for zinc orthophosphate with a passivation dose of 3.0 mg/L and a maintenance dose of 1.0 mg/L is provided in **Table 8-1**. Tanks will be double-walled for containment.

Table 8-1 – Initial Tank Sizing for Orthophosphate Feed System

Scenario	Dose (mg/L)	Storage (gallons)	Days of Storage at Average Flow (55 mgd)	Days of Storage at Max Flow (80 mgd)
Initial Passivation Dose (Temporary)	3.0 mg/L	5,000	14 (348 gpd)	10 (506 gpd)
Maintenance Dose (Permanent)	1.0 mg/L	4,000	34.5 (116 gpd)	24 (169 gpd)

A concurrent pipe loop demonstration study is recommended to be performed in parallel with full-scale implementation of the orthophosphate feed system to optimize treatment by studying factors such as pH and dose of the orthophosphate. Details of the recommended pipe loop demonstration study are discussed in Section 8.4.

In dosing orthophosphate, an increase in phosphorous and zinc concentrations will occur in the wastewaters collected in Newark and other communities using the Newark's water. Owners of wastewater treatment facilities that will encounter increased phosphorous concentrations will need to be notified to determine any potential implications to NJPDES permit compliance that may result from the orthophosphate chemical addition.

8.2 Chemical Feed Location Recommendations

As mentioned in Section 2, the Cedar Grove Reservoir is an open, finished water reservoir. Dosing of orthophosphate into an open reservoir will increase phosphorus concentrations. Phosphorus is a nutrient that stimulates algal growth, which cause algal blooms. The New Jersey Surface Water Criteria for total phosphorus in freshwater reservoirs and lakes is a maximum of 0.05 mg/L. In view of this, CDM Smith recommends dosing orthophosphate at the Valley Road Rechlorination Station located in Montclair, downstream of the Cedar Grove Reservoir and just north of Newark's distribution. Sodium hypochlorite is dosed at this location and pH and chlorine residual are monitored on site. Newark staff indicated that an operator visits this location twice per day.

Based on an initial site visit, it does not appear that an orthophosphate chemical bulk storage tank would fit within the existing building. In the interest of dosing orthophosphate as quickly as possible, the orthophosphate chemical storage tank can be located outside with heat tracing to prevent the chemical from freezing. Temporarily locating a tank on the existing driveway will expedite the process of feeding orthophosphate in the drinking water. The tank would need to be

designed to handle wind loads and be properly anchored. Additional security features at the site may be needed to protect the outdoor storage tank.

The remainder of the feed system, including two metering pumps (one duty, one standby), control panels and variable frequency drives (VFDs), can fit within the available footprint in existing basement. Orthophosphate would be injected into the pipe adjacent to the existing chlorine injection for rechlorination. The dosing would be flow-paced with the existing venturi meter to maintain a consistent dose.

An evaluation of all users supplied by the Pequannock WTP upstream of the Cedar Grove Reservoir is required to determine if any satellite orthophosphate feed systems will be necessary in addition to the Valley Road Rechlorination Station feed system.

8.3 Distribution System pH Recommendation

Currently, the average pH at the Valley Road Rechlorination Station is approximately 7.1 at the POE into the distribution system. The EPA OCCT Guidance Manual, confirmed by full-scale experience, recommends a pH range of 7.2 to 7.8 for orthophosphate addition (US Environmental Protection Agency, 2016); however, every system is unique with respect to its optimal pH range. With the pH variability known to occur in the City's distribution system, it is recommended that Newark aim to achieve a slightly higher pH, in the interim, of approximately 7.3 to 7.4 leaving the Valley Road Rechlorination Station to stay above pH 7.2 in the far reaches of the distribution system. At a pH below 7.2, the orthophosphate will be slower to react and will not be as effective in reducing lead solubility. Newark has provided a plan to NJDEP to meet simultaneous compliance of primary disinfection, disinfection byproducts and corrosion control. If pH must remain low at the Pequannock WTP for compliance reasons, a satellite sodium hydroxide chemical feed system can be installed at the Valley Road Rechlorination Station to raise pH in the distribution system to improve corrosion control.

In the long-term, if Newark can improve its removal of disinfection byproduct precursors and find a suitable means of assuring primary disinfection, then pH can be increased further to a more effective range for orthophosphate, likely between 7.5 and 7.8. The optimal pH range for Newark's water can be evaluated in the loop study discussed in Section 8.4.

To achieve the recommended pH values of 7.3 to 7.4 without sodium silicate in all seasons, a lime dose of approximately 12 to 15 mg/L would be required. It is recommended that sodium silicate continue to be used as a pH adjustment chemical until the lime feed system is operated at these higher dosages. Sodium silicate use should also be continued until the pilot loop study can evaluate whether there will be any negative impacts of discontinuing the silicate application in the distribution system.

Maintaining a consistent pH is as important as the actual pH level itself. In the month of July 2018, daily pH at the Valley Road Rechlorination Station fluctuated between pH 6.29 and 7.65. This is an extreme variation in pH values over a 31-day period. Furthermore, the pH range throughout the distribution system is even more extreme than the values measured at the distribution system POE. As of the finalization of this report in March 2019, Newark has stabilized pH at the Pequannock WTP. If variations are experienced in the distribution system or if the pH is

consistently below the optimal pH range for zinc orthophosphate, it is recommended that Newark install a satellite sodium hydroxide feed system.

8.4 Demonstration Pipe Loop Study

To optimize the addition of orthophosphate to Newark's distribution system, a pipe loop demonstration study should be performed. However, in the interest of public health protection, it is not recommended that full-scale implementation of orthophosphate addition be delayed until after the pipe loop study is completed. In parallel with full-scale implementation of orthophosphate addition, the pipe loop study would evaluate parameters such as:

- Optimal PO₄ dose
- Optimal pH
- Change in pH adjustment chemical (i.e., replacing sodium silicate with an alternative alkaline chemical)

A protocol for the pipe loop study will be developed in conjunction with Newark and provided to NJDEP for review prior to commencing the study. In general, the study could include one rack of three or four pipe loops to be installed at the Pequannock WTP. Each loop would contain a section of excavated lead service line from Newark's distribution system. A portion of each LSL would also be sent to EPA for analysis of the pipe scales to document baseline conditions. Scale analyses would then be conducted on the pipe segments within the loops later in the study to correlate actual scale deposits with the water chemistry conditions. During development of the study protocol, the need to condition the pipe segments at the start of the study using Newark's current finished water would be determined. If conditioning is performed, then, after a short period of initial conditioning, all but one loop would be modified to evaluate the different parameters enumerated above. The remaining pipe loop would continue to represent existing water chemistry conditions as a "control." Sampling is expected to include total and dissolved lead, pH, ORP, chlorine, alkalinity, orthophosphate residual, silica residual and aesthetic water quality parameters such as iron and manganese. A detailed sampling plan would be prepared as part of the study protocol development.

It was confirmed with the EPA in September 2018 that there has not been a successful pipe loop study involving excavated lead pipe containing tetravalent lead scales that have returned to "existing conditions" after a period of conditioning. Once lead pipes with tetravalent lead scales are excavated and disturbed, they continue to behave erratically with an increased release of particulate lead. For this reason, the incorporation of a conditioning period (and the duration of that period) would be evaluated as part of the study protocol development. It may be that, instead of running an extended conditioning period for the loops, CCT modifications will be introduced while the pipes are releasing high levels of particulate lead. CCT solutions that are effective for such a "worst case" condition in the pipe loop study would be anticipated to be effective in the distribution system under the same water chemistry conditions.

As mentioned in Section 5, additional pipes in the West Ward, Central Ward and East Ward are recommended to be excavated and sections sent to the EPA for scale analysis and comparison with the scales already analyzed.

8.5 Implementation Schedule

Newark is proceeding with procurement and construction of a temporary feed system to expedite the dosing of the orthophosphate in the drinking water. It is estimated that the orthophosphate system could be installed and operating by the second quarter of 2019 with the construction of a temporary feed system.

Anticipated completion schedule for efforts related to this improvement project include:

- 4-6 weeks for design and submission of a permit application to NJDEP
- 2-4 weeks for NJDEP review and approval of a Bureau of Safe Drinking Water Permit
- 3-4 months for procurement and construction (providing 8-12 weeks for tank and control panel lead time from approved shop drawings)
- 4-6 weeks installation and operation

It is anticipated that the pipe loop study could be placed into operation prior to the start-up of the proposed orthophosphate system. During this time, the initial introduction of orthophosphate into the lead pipes can be closely monitored to better predict anticipated behavior in the distribution system prior to introducing to the full Pequannock supply.

The permanent system will include buried permanent tanks and require a site plan approval from Montclair. It will be constructed while the temporary system is continuously feeding orthophosphate. The cost of the permanent orthophosphate system as described herein is estimated to be approximately \$800,000 including engineering, materials, labor and equipment. This assumes that the bulk storage tank would be outside in a vault and not housed in a building.

8.6 Monitoring During Implementation

To monitor changes in water chemistry due to the full-scale addition of orthophosphate in the distribution system, it is recommended that a targeted monitoring program be developed and executed. The purpose of the monitoring program is to assess the progression of orthophosphate residual levels in the system, as well as to determine if any adverse water quality effects are occurring as a result of the change in treatment. It is anticipated that sampling would be conducted monthly or more frequently as lead concentrations decrease and stabilize. Flowing samples would be collected from routine coliform sampling sites and analyzed for parameters such as pH, alkalinity, chlorine residual, ORP, color (apparent), turbidity, iron (total and dissolved), manganese (total and dissolved), coliform, HPC, silica and orthophosphate residual. First-draw tap sampling, as well as sequential sampling (discussed below), would be performed periodically at homes with lead service lines selected from the sampling pool for LCR compliance.

In addition, Newark's Water Quality Parameter Sampling Plan will be updated to include monitoring of orthophosphate residual, as well as continuing to monitor pH and chlorine residual. The results from the sampling will be reviewed on an ongoing basis to monitor changes in the distribution system and the sampling program (and treatment) will be adjusted, as necessary.

8.6.1 Sequential Sampling – Before and During Implementation

It is recommended that Newark perform additional sequential sampling to evaluate conditions in the wards not yet tested. This would include the West Ward (Pequannock-supply), Central Ward (potential mix of both Pequannock-supply and Wanaque-supply), and the East Ward (Wanaque-supply). In addition, it is recommended that, as part of Newark's monitoring plan, sequential sampling (measurement of lead profiles), as presented in Section 4, continue to be performed after orthophosphate addition is implemented. The sequential sampling would be performed at homes with lead service lines and lead solder to evaluate the effectiveness of the orthophosphate in reducing dissolved and particulate lead concentrations throughout the service line, including all contributing factors. It is recommended that such sequential sampling be performed at a couple of homes that are easily accessible and will remain with a lead service line for at least the next year. Sampling would be performed at the select homes prior to commencing dosing of orthophosphate and then once every month after orthophosphate is implemented until the lead results stabilize.

8.7 Additional Recommendations

The following are additional recommendations for a holistic approach to improving Newark's water quality.

8.7.1 Short-Term Recommendations

As indicated in this report, there is evidence that protective lead scales that have formed on lead service lines and lead components within premise plumbing in the Newark distribution system have been destabilizing and are porous, allowing lead to be released into the drinking water. Health risks exist for customers with lead service lines and for customers with premise plumbing components that contain lead, such as lead solder, galvanized plumbing and/or brass fittings with lead content. Health risks are greatest for infants, young children, pregnant women and adults with kidney problems or high blood pressure.

The EPA guide, Implementing the Lead Public Education Provision of the Lead and Copper Rule, dated June 2008, should be used as guidance for providing public education and to reach the most vulnerable populations. Other resources are available from the American Water Works Association and the Lead Service Line Replacement (LSLR) Collaborative.

For customers in Newark, utilization of point-of-use filters is the recommended approach to minimize lead exposure through the removal of particulate lead. Filters are recommended until the new orthophosphate system can substantially decrease both dissolved and particulate lead prior to and during the initial passivation period of the orthophosphate. Filters are recommended to help protect customers both in homes with lead service lines and in homes with interior plumbing that contain lead solder, galvanized piping or brass fittings with lead content. Filters are recommended over promoting flushing of premise plumbing since, at this time, the scales are unstable and can be easily disturbed potentially releasing particulate lead during flushing. Point-of-use filters should be NSF 53 and NSF 42 certified for lead removal (NSF/ANSI 53: Drinking Water Treatment Units - Health Effects).

If Newark provides residents with point-of-use filters, the program should provide specific guidance to the customers regarding replacement of the filters at the frequency recommended by

the manufacturer. Risk of contamination can be increased if filters are not properly maintained and replaced regularly.

It is noted that it is expected that Newark will continue to exceed the Lead Action Level until the orthophosphate is dosed at the Valley Road Rechlorination Station and has had time to passivate the system and build a protective barrier to prevent lead from leaching into the water.

8.7.2 Long-Term Recommendations

In considering a holistic approach to achieve simultaneous compliance with all drinking water regulations, it is recommended that Newark evaluate alternatives for the following process modifications:

- **Stabilization of pH in the distribution system.** Stabilizing the pH will help improve water quality. Stabilization may include upgraded chemical feed equipment and monitoring at the Pequannock WTP, pH adjustment at the Valley Road Rechlorination Station, and/or improved monitoring and flushing in the distribution system to maintain a consistent pH from the North Ward to the South Ward.
- **Removal of disinfection byproduct precursors.** Improving filter performance and/or the addition of a clarification process would reduce the organic carbon concentration during treatment and help Newark achieve compliance with the Stage 2 Disinfection Byproducts Rule. Newark has submitted a plan to NJDEP to reduce disinfection byproduct precursors. The upgrades are planned to be in operation in April 2019.
- **Utilizing an alternate primary disinfectant.** An alternate primary disinfection process, such as ozone, may help Newark meet primary disinfection requirements as well as reduce disinfection byproduct formation.

8.8 Impacts on Consecutive Systems

As part of the changes to the water system, Newark will coordinate with any other townships that receive water from the Pequannock supply. Pequannock Township receives water upstream of the proposed orthophosphate addition while all other systems are fed downstream of the proposed orthophosphate addition location. Newark has reviewed the proposed changes to the CCT inhibitor and pH adjustment with the Pequannock Water Department. . The need for a satellite orthophosphate feed system will be evaluated and discussed with the Pequannock Water Department, however, the Pequannock Water Department currently does not have any lead issues.

Newark's consecutive systems downstream of the Valley Road Rechlorination Station are anticipated to benefit from the changes being proposed to the CCT at the Pequannock WTP. The following summarizes the anticipated impact to each system:

- Belleville Water Department – will transition from sodium silicate to orthophosphate simultaneously with Newark. The transition will be coordinated to encourage Belleville to flush the mains prior to the transition to remove sediment in the pipe and during the transition to help passivate the system. If the dose of orthophosphate from Newark is diluted, a satellite feed system for Belleville may be recommended.

- Bloomfield Water Department – will transition from sodium silicate to orthophosphate simultaneously with Newark. The transition will be coordinated to encourage Bloomfield to flush the mains prior to the transition to remove sediment in the pipe and during the transition to help passivate the system. If the dose of orthophosphate from Newark is diluted, a satellite feed system for Bloomfield may be recommended.
- City of Elizabeth (c/o New Jersey American Water – Liberty) – already doses orthophosphate, which is currently supplied from the Wanaque source. The CCT proposed at the Pequannock supply will not have an impact on the City of Elizabeth system.
- Nutley Township – will transition from sodium silicate to orthophosphate simultaneously with Newark. The transition will be coordinated to encourage Nutley to flush the mains prior to the transition to remove sediment in the pipe and during the transition to help passivate the system. If the dose of orthophosphate from Newark is diluted, a satellite feed system for Nutley may be recommended.
- All other interconnections with Newark are either on the Wanaque Gradient or used on an emergency basis only. Most of the systems with emergency interconnections with Newark utilize an orthophosphate chemical for corrosion control. With the addition of orthophosphate at the Pequannock WTP, the orthophosphate residual concentration in these systems will be more consistent when purchasing water from Newark.
- The areas experiencing blending between the Pequannock and Wanaque Gradients will benefit from a more stable orthophosphate residual coming from both the Pequannock and Wanaque Gradients.

Each consecutive system will be notified of the treatment changes at Newark via a letter explaining the change and recommendations for monitoring and flushing prior to implementation and documentation of the notification will be provided to NJDEP. The systems will be notified 30 days in advance of the transition to zinc orthophosphate and a reminder will be provided at least five (5) days prior to the transition. The City will schedule a meeting with the consecutive systems mentioned above to discuss the project and procedures in detail.

8.9 Recommendations Summary

Table 8-2 summarizes the recommendations presented in this report for the Pequannock service area.

Table 8-2 – Summary of CCT Recommendations for Pequannock

Factor	Immediate CCT Recommendation	Longer Term CCT Recommendation	Additional Notes
Chemical	Zinc Orthophosphate	Zinc Orthophosphate	
Dosage	0.5 mg/L as PO ₄ increasing to passivation dose of 3.0 mg/L as PO ₄	Minimum 1.0 mg/L as PO ₄ (or as determined by pipe loop study)	Evaluate dosage in pipe loop study
Feed Location	Valley Road Rechlorination Station	Valley Road Rechlorination Station	
System pH	Stabilize pH to 7.3 to 7.4	Stabilize pH to optimal pH from pipe loop study	Evaluate optimal pH in pipe loop study
Sodium Silicate	Maintain current dose	Replace with a more cost-effective pH adjustment chemical	Evaluate any negative impacts from eliminating sodium silicate addition in pipe loop study
Demonstration Study	Conduct pipe loop study in parallel with implementation of immediate addition of zinc orthophosphate	Apply results of pipe loop study to long-term CCT plan	
Monitoring	Implement representative monitoring program, including sequential sampling	Continue monitoring program and sequential sampling until conditions are stabilized	
Public Health	Point-of-use filters and conduct public education program	CCT optimization and LSL Replacement Program	

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